

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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THE ASSESSMENT
OF THE INFLUENCE OF SOLAR STORMING
ON GEODETIC COORDINATES DETERMINED
BY GLOBAL NAVIGATION SATELLITE SYSTEM

DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES,
MEASUREMENT ENGINEERING (10T)



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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

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Abstract

Solar storms are the big error source affecting global navigation satellite system (GNSS) satellites' orbits. Navigation and positioning systems are affected, in one way or another, by different kinds of solar storms. Much work has been done to investigate and model the extent of the errors produced by solar activity. However, most research has concentrated on ionospheric errors because these are thought to be most significant. So we think that the influence of the solar activity to the accuracy of the global navigation satellite system is not enough investigated.

The dissertation consists of an introduction, four chapters and general conclusions. The introduction presents the problem and its topicality. The purposes and task of the work are formulated, and the methods used and the novelty of solutions is described. The author's publications and structure of the thesis are presented.

Chapter 1 deals with the review of scientific literature. This chapter covers the major components of the field of solar storm activities studies, describes the current state of knowledge in this field, and presents some analysis and results that are necessary as theoretical background for the study of space weather activity and relationship to ground positioning.

Chapter 2 concerns the relevant theoretical issues. This chapter provides a review of the necessary orbital theory to introduce the methods to obtain GNSS satellite and ground receiver positions, as well as demonstrating the idea of finding out which satellites are in eclipse.

Chapter 3 deals with the analysis of the satellite's orbit changes in the zone of the Earth's shadow. The original algorithms and computer procedures for the detection of the satellites in the zone of eclipse are presented.

Chapter 4 gives an account of the investigations and determinations of the effects of specific solar storming events to vector positioning on the Earth surface. Author presents an original suggestion to distinguish vectors to short, middle length and long. The dissertation investigates the errors that are caused due to inaccuracies in the orbital parameters transmitted by the satellites. The orbital parameters transmitted by the satellites are compared with precise satellites' orbits, and calculated vector's components – with the most reliable values. Finally, the influence of the solar storming events on the precision of the point's geodetic coordinates is shown.

The author has published six articles related to these issues, i.e. five articles in reviewed scientific periodical publications; one article in of the proceedings of the international conference, while there was made six presentations at conferences.

Reziumė

Saulės audros daro didžiulę įtaką globalinės navigacinės palydovinės sistemos palydovų orbitoms. Navigacinės ir padėties nustatymo sistemoms vienaip ar kitaip turi įtakos skirtingų rūšių Saulės audros. Daug nuveikta tiriant ir modeliuojant Saulės aktyvumo iššauktų klaidų mastus. Didelė dalis mokslinių tyrimų yra sutelkta į jonosferos sukeltus klaidų šaltinius, nes buvo galvojama, kad jų įtaka yra didžiausia. Tačiau Saulės aktyvumo įtaka globalinės navigacinės palydovinės sistemos tikslumui, nėra pakankamai ištirta.

Disertaciją sudaro įvadas, keturi skyriai ir rezultatų apibendrinimas.

Įvadiniame skyriuje pagrindžiama tiriamoji problema, apibrėžiamas problemos aktualumas, formuluojamas darbo tikslas bei uždaviniai, aprašomas mokslinis darbo naujumas, pateikiami ginamieji disertacijos teiginiai pristatomos autoriaus publikacijos ir pranešimai konferencijose, aprašoma disertacijos struktūra.

Pirmasis skyrius skirtas mokslinės literatūros analizei. Jame nagrinėjami Saulės audrų įtakos navigacinėms palydovinėms sistemoms pagrindiniai komponentai, apibūdinamas dabartinių žinių lygis šioje srityje, pateikta su numatytais tyrimais susijusi analizė ir rezultatai, kurie yra būtini kaip teorinis pagrindas kosmoso oro aktyvumui ir sąsajoms su padėties nustatymu ant žemės paviršiaus tirti.

Antrajame disertacijos skyriuje pateiktas atitinkantis tyrimų sričiai teorinis tyrimas. Pateikiama reikiami kosminės geodezijos metodai, siekiant nustatyti dirbtinių Žemės palydovų (DŽP) ir imtuvų ant žemės paviršiaus padėtis, taip pat pateikiamas metodas palydovams Žemės šešėlio zonoje nustatyti.

Trečiajame disertacijos skyriuje analizuojama DŽP orbitos kitimas palydovui esant Žemės šešėlio zonoje. Pateikiami originalūs algoritmai ir kompiuterinės procedūros palydovų užtemimų zonoms nustatyti.

Ketvirtajame disertacijos skyriuje pateikta analizė konkrečių Saulės audrų įtaka vektorių nustatymui ant Žemės paviršiaus. Autorė pristato siūlymus išskirti trumpo, vidutinio ir ilgo atstumo vektorius. Disertacijoje yra nagrinėjamos klaidos, atsiradusios dėl transliuojamų palydovų perduodamų orbitų parametrų netikslumų. Transliuojami palydovų orbitų parametrai yra lyginami su tikslųjų orbitų elementais, o apskaičiuotų vektorių komponentai – su patikimiausiomis jų reikšmėmis.

Disertacijos tema paskelbti šeši straipsniai: penki – tarptautinėse duomenų bazėse referuojamuose žurnaluose; vienas – kitose tarptautinių ir respublikinių konferencijų medžiagose, perskaityti šeši pranešimai konferencijose.

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Introduction

The Investigated Problem

Since the beginning of positioning on the Earth's surface by using satellites, the challenge has been to eliminate and correct sources that affect positioning accuracy. Mathematical solutions have been found to reduce these errors as much as possible. Some of the errors can be totally eliminated, while others can be corrected to a certain degree. Some of the errors, such as ionospheric errors, are still being examined and modelled.

When a ground receiver determines its position, there are many possible sources of errors and uncertainties:

- Ionospheric and tropospheric delays – signal delays due to the signal passing through the atmosphere;
- Orbital errors (ephemeris errors) – errors caused due to satellites transmitting inaccurate orbit parameters;
- Signal multipath – this error can occur when signals are reflected off objects (buildings, hill, etc.), before reaching receivers;
- Satellite clock errors – errors in the timing systems of the satellites themselves;

- Receiver clock errors – the receiver clock is not as accurate as the atomic clocks on the satellite, which can lead to timing errors.

Number of satellite visible – accuracy is better if the receiver observes more satellites: (Seeber 1993)

- Geometry of the satellites – relative position of the satellites in the sky affects the accuracy, best if the satellites are spread widely.

Some of the methods used to find out ways to eliminate these errors are:

1. Differencing;
2. Using more signal frequencies;
3. Modelling ionospheric errors.

Ionosphere and troposphere delays and orbit errors are affected by the level of solar storm activity (Langley 2000). It is generally assumed that satellite orbit errors are eliminated by differencing (using two or more receivers simultaneously) and by using more signal frequencies.

The intensity of solar storm activity varies according to a well established 11–12 year cycle. There are records of sunspot activity covering several hundred years.

The solar cycle is just embarking (at the time of writing) on the upward leg of its cycle, and the next solar cycle high is confidently predicted in 2013. Further, there have been widespread and respectable reports that this coming cycle is expected to be about 50% more intensive than the previous cycle. Extensive details on the science of solar activity as well as current intensity levels are obtainable at the Space Weather Prediction Center (SWPC). These details have become available as a result of enormous investment in the launching of specialized solar observation missions, clearly justified by society's increasing dependence on space-based communication technologies. As explained at SWPC and below, solar storming levels have now been categorized as far as they can affect human society, and these can be seen in detail at the SWPC web site.

The fact that the above mentioned solar storming phenomena can affect satellite navigation leads clearly and obviously to the consequence that these effects can also disturb attempts by surveyors to determine positions with high (centimetric) precision.

The situation is further complicated by the consequences of satellites passing through eclipse. If the Sun is active, then all satellites visible to the Sun can be assumed to be similarly affected. GNSS satellites in partial eclipse might be less affected, while those actually in full umbra would logically be completely unaffected. Therefore, the question arises as to what effect there might be on ground receiver's positions.

Importance of the Thesis

Solar radiation pressure is the largest error affecting Global Navigation Satellite System (GNSS) orbit and recent events have been widely reported (Springer, Beutler and Rothacher 1999). Navigation and positioning systems are affected, in one way or another, by different kinds of solar storms. Surveyors and other technicians who require high accuracy GNSS measurements are therefore likely to be most affected by these errors. Much work has been done to investigate and model the extent of the errors produced by solar activity. Most of the research has concentrated on ionospheric errors because these are thought to be most significant.

Conversely, this work examines the errors that are caused due to inaccuracies in the orbital parameters transmitted by the satellites. The precise coordinates of each observed satellite are needed in order to be able to calculate the correct positions of the ground receivers. These coordinates are computed using *a priori* parameters transmitted by the satellites. However, the exact location of the satellite can subsequently be calculated using orbital parameters from ephemerides, which are obtained *a posteriori* from tracking observations.

The most significant disturbance of satellites' locations happens due to high solar pressure. During these periods the satellites can physically be pushed off course, thus leading to potentially very big ephemeris errors. Of course, these errors might vary according to the orientation of the satellites' instantaneous position, and whether or not they might be in Earth shadow, that is, in eclipse. Meanwhile, there are many ground control stations which observe the satellites and calculate their precise *a posteriori* orbit locations. High precision GNSS satellite ephemerides are freely available from the International GNSS Service (IGS).

The National Oceanographic and Atmospheric Administration (NOAA) in USA has introduced so-called "Space Weather Scales" which are used to improve understanding and inform the general public and technical operations about current and future space weather conditions. These scales have been introduced to show the effects that can be experienced due to space environment disturbances.

The Object of Research

The main object of the research is an examination of the influence of solar activity on GNSS satellites' orbits, and, as a consequence, on the accuracy of the ground positions. The examination includes consideration of Earth's shadowing (i.e. satellites in eclipse) under solar storming conditions.

The Goal of the Thesis

The main goal of this thesis is to examine whether the error in satellites' orbital locations due to solar activity can affect the accuracy of the positions detected by ground receivers, including consideration of the effects of satellites in Earth's shadow.

The Tasks of the Thesis

To achieve the objective, the following tasks need to be addressed:

1. To study technical literature to acquire and structure knowledge in research field, related to an examination of the influence of solar activity on GNSS satellite's orbits, and, as a consequence, on the accuracy of the ground positioning.
2. To prepare computerized procedures to determine satellites positions and satellites in Earth's shadow.
3. To study effects of solar storming on GNSS satellite's orbits in the context of the satellites' passage through Earth's shadow.
4. To study the effects of solar storming on GNSS satellites' orbits, including the effects of solar storming on receiver observable comparisons.

Research Methodology

Theoretical and experimental studies to determine solar storms' effects on GNSS using satellite positions in orbit determination, computation of receiver positions theory, and availability of GNSS satellites while they are in Earth's shadow.

Importance of Scientific Novelty

Preliminary literature searches and studies quickly showed that enormous research efforts have been used to examine satellite-positioning errors due to atmospheric effects. Somewhat less appears to have been reported concerning errors arising from orbital disturbance. At the same time, high precision observational techniques on the Earth's surface do not appear to take account of potential orbital errors. As an example, modern field receivers do not normally

have the user command ability to not use specific satellites if the user considers it appropriate. Perhaps such ability would be advisable, particularly having regard to potential eclipse effects.

Thus, orbital errors and their consequences need to be systematically studied and assessed through the tasks mentioned above in order to determine the importance of introducing mitigating procedures to high precision practices.

1. Tests were made of the influence of specific solar storms on geodetic coordinates determined by GNSS using precise and broadcast ephemerides. Differences were evaluated to examine the extent of solar storming effects on satellite positions in their orbits, and how big differences appear when calculating receiver position. Significant variations in geodetic positions correlated with specific solar storming events were shown.
2. The results of satellites being in eclipse were also analysed and found to affect the quality of positioning when satellite is in use. However, no significant variations emerged clearly.

Practical Significance of Achieved Results

The application of the investigation has been used to assess the impact of solar storms and eclipsed satellites on geodetic measurements and to evaluate the accuracy of the measurements. Also, to improve the computerized procedures for the GNSS geodetic measurements treatment.

The Defended Statements

1. The solar storming events influence on the satellites coordinates is impossible to distinguish by the comparison of the broadcast and precise ephemerides. Significant differences between two sets of satellites coordinates – broadcast and precise – were found. But it is suggested that these large differences might be due to residual errors in the predicted broadcast ephemerides, compounded by the unavoidable effects of “normal” (i.e. under non solar storming conditions) space phenomena such as various forms of cosmic radiation pressures and gravity field fluctuations.
2. The solar storming events have influence to the accuracy of the ground positioning vectors. The errors range approximately till 50 mm for the short vectors, and up to 800 mm for the mid and long vectors.

3. The effect of Earth's shadowing on a satellite positioning is not significant, because the differences of ephemerides of satellites passing the Earth's shadow do not show changes. Also, evaluations show that there are just one or two satellites in Earth's shadow at the same time.
4. The solar storming events have influence to the accuracy of the geodetic coordinates of the points on the Earth's surface. For example, the quality of computed geodetic coordinates of some CPOS station ranged from 1 mm to 6 mm, whereas the errors in geodetic coordinates, when is reported Solar storm activity, ranged from 2 mm to 16 mm.

Approval of the Results

The author with the co-authors has published six scientific papers: five articles in reviewed scientific periodical publications (Preiss, Zubinaite, 2010a; Zubinaite, Preiss 2010b; Zubinaite, Preiss 2010c; Zubinaite, Preiss, 2011a; Zubinaite, Preiss, 2011b); one article was published in the proceedings of the international conference (Preiss, Zubinaite, 2011).

The author has participated and presented her research at six scientific conferences:

1. International conference „Aviation“ 2009 in Vilnius;
2. Scientific conference „Aviation“ 2010, 2011, 2012 in Vilnius;
3. International conference „The 8th International Conference, Environmental Engineering“ 2011 in Vilnius;
4. Scientific conference „Civilinė inžinerija ir geodezija“ 2011 in Vilnius.

Dissertation Structure

The research consists of the following parts, namely the introduction, four chapters and summary of the results, five supplements are included as well.

The dissertation contains 88 pages, apart from the supplements; there were used 19 numbered equations, 40 figures and 11 tables. 113 literature sources were used.

Problems of Solar Storm's Effects to the Geodetic Measurements Valuation

This chapter reviews the theory of solar storming, looking at the history and examining current assessment methods and their accuracy. Scientific literature on space weather effects on the Global Navigation Satellite System and geodetic issues is examined.

1.1. Historical Overview of the Solar Storms Effects Investigation

The study of the Sun has been pushed by revolutionary scientific discoveries. Early indirect observations of the Sun, using a telescope, allowed scientific study of the Sun showing that the Sun is a dynamic, changing body. The development of spectroscopy and the discovery of elementary particles and nuclear fusion allowed scientists to begin to understand the composition of the Sun and the processes that fuel it. The development of artificial satellites and other spacecraft finally allowed scientists to study the sun from space, allowing

a full view of all of the Sun's radiation and a continuous study of the Sun (Poppe, Jorden 2006).

The oldest eclipse record is found on a clay tablet uncovered in the ancient city of Ugarit, (in what is now Syria), with two plausible dates usually cited: 3 May 1375 BC or 5 March 1223 BC, the latter being favored by most recent authors on the topic. It is certainly clear that by the eighth century BC, the Babylonians were keeping a systematic record of solar eclipses, and may even have been able to predict them fairly accurately based on numerical rules (Fotheringham 1933; Ziker 1995; Morrison, Stephenson 2001).

The two oldest records of a sunspot observation are found in the *Book of Changes*, probably the oldest extant Chinese book, compiled around or before 800 BC. Astronomers at the court of the Chinese and Korean emperors made regular notes of sunspots. It seems, however, that observations were not carried out systematically for their own sake, but instead took place whenever astrological prognostication was demanded by the emperor. The surviving sunspot records, though patchy, were made before telescopes had been invented (Mossman 1989; Stephenson 1990; Hetherington 1996).

Greek philosopher Aristotle (384–322) was the first known person to use a device that allowed indirect observation of the Sun. Sometime between 384 BC and 322 BC Aristotle noticed that a hole in a screen would create an image of the Sun on the ground, if the screen were between the Sun and the ground. He made a simple version of a device called a camera obscura to take advantage of this effect. A camera obscura is still a popular way to observe solar eclipses. Also, an essential feature is the place occupied by the earth at the center of the Universe, with the Sun, planets and sphere of fixed stars revolving about that center, the Sun occupying the fourth sphere. In this geocentric model the Earth is absolutely fixed, with the motions of precession and daily rotation ascribed to the two outermost spheres of the model (Grant 1977; Crowe 1990; Pedersen 1993).

This basic planetary arrangement formed the basis of the mathematical model of planetary motion developed four centuries later by Claudius Ptolemy (ca. 100–170). In Aristotle's scheme there existed fundamental physical differences between the terrestrial and celestial realms, as demarcated by the Moon's sphere

The first mathematically-based attempt at determining the Sun-Earth distance is due to Aristarchus of Samos (ca. 310–230 BC) (Van Helden 1985; Hirschfeld 2001).

While the solar corona is visible at any solar eclipse the first explicit mention of what can be perhaps ambiguously interpreted to be the corona was made by the Byzantine historian Leo Diaconus (ca. 950–994), as he observed the

total eclipse of 22 December 968 from Constantinople (now Istanbul, Turkey) (Hetherington 1996; Van Helden 1996).

The cosmos of the late Christian medieval era was a fusion of ideas combining the physics of Aristotle and the planetary astronomy of Ptolemy. This is the world view that was destroyed in the sixteen and seventeenth centuries. The first blow was dealt by Nicholas Copernicus (1473–1542). He presented a new planetary model with the Sun placed in center, and letting all planets (including the Earth) orbit around the Sun. Copernicus also gave the Earth two additional motions: a daily axial rotation, and a precession of that spin axis. In doing so, Copernicus eliminated the need for the two outermost spheres of the ptolemaic model and produced a system where the speed of revolution decreases gradually outward all the way to the fixed stars (Sviatsky 1923; Kuhn 1957; Boas 1962; Gingerich 1993; Grant 1994; Hetherington 1996).

An early convert to the Copernican system was Johannes Kepler (1571–1630). After ten years of laborious work using the accurate observations of planetary positions accumulated over 20 years by the astronomer Tycho Brache (1546–1601), Kepler came to realize that the orbital paths of planets have the form of ellipses with the Sun at one focus, and that the radius vector joining a given planet to the Sun sweeps equal areas in equal time (the well known Kepler's Laws) (Thoren 1989; Gingerich 1989; Gingerich Voelkel 1998).

Italian scientist Galileo observed the Sun with a telescope for the first time in 1610. When Galileo first observed the Sun in detail, he saw dark spots on its surface, carried around by the Sun's rotation. For centuries astronomers wondered whether they were clouds floating in the Sun's atmosphere, but they really were huge regions of magnetic field, about as intense as the field at the poles of an iron magnet (Shea 1970; Drakes 1978; Aiton 1989).

Sunspot observations continued in the seventeenth century, with the most active observers being the German Johannes Hevelius (1611–1687) and the French Jesuit Jean Picard (1620–1682). Very few sunspots were observed from about 1645 to 1715, and when they were, their presence was recorded as a noteworthy event by active astronomers. At that time, a systematic solar observing program was underway under the direction of Jean Dominique Cassini (1625–1712) at the newly founded Observatoire de Paris, with first Picard and later Philippe La Hire carrying out the bulk of the observations. Historical reconstructions of sunspot numbers indicate that the dearth of sunspots is real, rather than the consequence of a lack of diligent observers. A simultaneous decrease in auroral counts further suggests that solar activity was greatly reduced during this time period.

This period is now known as the Maunder minimum, after the solar astronomer E. W. Maunder, who, following the pioneering historical investigations of Gustav Spörer (1822–1895), was most active and steadfast in

investigating the dearth of sunspot sightings by astronomers active in the second half of the seventeenth century. The documented occurrence of exceptionally cold winters throughout Europe during those years may be causally related to reduce solar activity, although this remains a topic of controversy (Eddy 1976, 1983; Ribes, Nesme-Ribes 1993; Hoyt, Schatten 1997).

The mass of the Sun and its distance from the Earth are two very fundamental quantities that were only determined with reasonable accuracy in the eighteenth century. The first quantitative estimate of the Sun's mass is due to Isaac Newton (1642–1727). Newton presented the calculation in his *Principia Mathematica*, making use of his newly formulated law of universal gravitation. Newton argued that stable planetary orbits resulted from a balance between centripetal and gravitational acceleration; in doing so he could finally provide a physical explanation for the three laws of planetary motions established empirically by Kepler. The ratio of Sun-to-Earth mass can be in principle determined, without knowing the actual value of the universal gravitational constant. This only required knowledge of orbital periods and radii. Newton, however, used too high a value for the solar parallax, thus grossly underestimating the Sun-Earth distance, and, consequently, underestimating the Sun-to-Earth mass ratio by more than a factor of ten ($M_{\text{Earth}}/M_{\text{Sun}}=28\,700$ instead of 332 945). In later editions of his *Principia* (in 1713 and 1726), Newton used improved estimates of the solar parallax, and brought his estimate to within a factor of two of the modern value (Wilson 1989; Hufbauer 1991).

In the 1660's Isaac Newton had shown that sunlight can be separated into separate chromatic components by refraction through a glass prism. In 1800, William Herschel extended Newton's experiment by demonstrating that invisible "rays" existed beyond the red end of the solar spectrum. He did so by detecting the temperature rise in thermometers placed beyond the red end of the visible spectrum (Meadows 1970).

Herschel boldly conjectured that these invisible calorific rays, later named infrared radiation, were fundamentally no different from visible light, and could not be seen simply because the eye is not sensitive to them. Herschel also sought calorific rays beyond the violet end of the spectrum, but to no avail. However, the following year, Johann Wilhelm Ritter (1776–1810) used an experimental setup similar to Herschel's, but placed beyond the violet end of the spectrum a piece of paper soaked in silver chloride; the subsequent blackening of the paper beyond the visible violet demonstrated the existence of ultraviolet radiation. The following year, and using similar photochemical means, William Hyde Wollaston (1766–1828) independently rediscovered ultraviolet radiation.

The solar constant is a measure of the sun's luminosity, and is defined by convention as the amount of energy incident per second on one square meter of

the outer terrestrial atmosphere, when the Earth is at a distance of one astronomical unit (149,598,500 km) from the Sun (Hufbauer 1991).

Although various scientists had attempted to calculate the Sun's energy output, the first attempts at a direct measurement were carried out independently and more or less simultaneously by the French physicist Claude Pouillet (1790–1868) and British astronomer John Herschel (1792–1871). Although they each designed different apparatus, the underlying principles were the same: a known mass of water is exposed to sunlight for a fixed period of time, and the accompanying rise in temperature recorded with a thermometer. The energy input rate from sunlight is then readily calculated, knowing the heat capacity of water. Their inferred value for the solar constant was about half the accepted modern value of 1367 ± 4 watts per square meter, because they failed to account for of absorption by the Earth's atmosphere (Hufbauer 1991).

As Schwabe's discovery of the sunspot cycle gained recognition, the question immediately arose as to whether the cycle could be traced further in the past on the basis of extant sunspot observations. In this endeavour the most active researcher was without doubt the Swiss astronomer Rudolf Wolf (1816–1893). Faced with the daunting task of comparing sunspot observations carried out by many different astronomers using various instruments and observing techniques, Wolf defined the parameter r , which continues to be used today and is now usually called the Wolf (or Zürich) sunspot number. Wolf succeeded in reliably reconstructing the variations in sunspot number as far as the 1755–1766 cycle, which has since been known conventionally as "Cycle 1", with all subsequent cycles numbered consecutively thereafter; at this writing (Hoyt, Schatten 1997, 1998), we are in the rising phase of cycle 24.

The solar cycle (or solar magnetic activity cycle) was discovered in 1843 by Samuel Heinrich Schwabe, who after 17 years of observations noticed a periodic variation in the average number of sunspots seen from year to year on the solar disk. Rudolf Wolf compiled and studied these and other observations, reconstructing the cycle back to 1745, eventually pushing these reconstructions to the earliest observations of sunspots by Galileo and contemporaries in the early seventeenth century. Starting with Wolf, solar astronomers have found it useful to define a standard sunspot number index, which continues to be used today (Charbonneau 2002).

In 1852, within a year of the publication of Schwabe's results in *Kosmos*, Edward Sabine (1788–1883) announced that the sunspot cycle period was "absolutely identical" to that of geomagnetic activity, for which reliable data had been accumulated since the mid-1830s. In fact three other researchers arrived at the same conclusion independently and more or less simultaneously: Rudolf Wolf (1816–1893) and Jean-Alfred Gautier (1793–1881), both in Switzerland,

and Johann von Lamont (1805–1879) in Germany. This marked the beginning of solar-terrestrial interaction studies (Hoyt, Schatten 1997).

On 1 September 1859, the amateur astronomer Richard C. Carrington (1826–1875) was engaged in his daily monitoring of sunspots, when he noticed two rapidly brightening patches of light near the middle of a sunspot group he was studying. In the following minutes the patches of light dimmed again while moving with respect to the active region, finally disappearing. This unusual event was also independently observed by R. Hodgson (1804–1872), another British astronomer.

The total solar eclipse of 18 July 1860 was probably the most thoroughly observed eclipse up to that time. Drawings were made including depictions of a peculiar feature in the SW (lower right) portion of the corona. Based on comparison with modern coronal observations, it is quite likely that these represent the first record of a Coronal Mass Ejection in progress (Eddy 1974).

This lucky observation represents the first clear description of a solar flare, corresponding to a sudden and intense heating of solar atmospheric plasma caused by reconnection of magnetic fields.

Both Carrington and Hodgson noted that magnetic monitoring instruments registered strong disturbances at about the same time, but it is not possible to tell for sure whether these were due to the flare they actually saw. It is more likely that they were caused by other generalized solar disturbances of which the flare was but one manifestation.

Great solar storms occur approximately once per decade. The list of the greatest solar storms over the past 150 years is presented below. The largest solar storm ever recorded occurred on 1–2 September 1859. It was the greatest solar storm in the past 450 years (Marusek 2007).

1–2 September, 1859 – also known as the Solar Superstorm, or the Carrington Event, which occurred during solar cycle 10. The Carrington Event of 1859 was the first documented event of a solar flare impacting Earth (Boteler 2006; Odenwald *et al.* 2008). The event occurred on September 1 and is named after British astronomer Richard Carrington, the solar astronomer who witnessed the event through his private observatory telescope and sketched the Sun's sunspots at the time. National Aeronautics and Space Administration (NASA) scientists have said that this flare was the largest documented solar storm in the last 500 years (Tyasto *et al.* 2009).

This storm was observed worldwide and is, historically, one of the greatest events recorded in the last 150 years. The storm of 1859 was the first event recorded by humans from a truly global perspective, not to be repeated until the eruption of Krakatoa in 1883 turned the sunsets red and crimson world-wide. Media were active in running extensive stories about the 1859 solar storm, and collecting reports from other countries (Nevanlinna 2006). The great

geomagnetic storm of 1859 is really composed of two closely spaced massive worldwide auroral events. The first event began on August 28th and the second began on September 2nd. It is the storm on September 2nd that results from the Carrington-Hodgson white light flare that occurred on the Sun on September 1st.

According to National Oceanic and Atmospheric Administration (NOAA), the Carrington solar storm event sparked major aurora displays that were visible as far south as the Caribbean. It also caused severe interruptions in global telegraph communications, even shocking some telegraph operators and sparking fires when discharges from the line ignited telegraph papers, according to a NASA description.

17–18 November, 1882. An extended period of strong geomagnetic activity was recorded during in solar cycle 12 (Tsurutani *et al.* 2006; Marusek 2007).

13–16 May, 1921 – The New York Railroad Storm. The prelude to this particular storm began with a major sunspot sighted on the limb of the sun vast enough to be seen with the naked eye through smoked glass. The spot was 94,000 miles long and 21,000 miles wide and by May 14th was near the center of the sun in prime location to unleash an earth-directed flare. The 3-degree magnetic bearing change among the five worst events recorded ended all communications traffic from the Atlantic Coast to the Mississippi. In the morning on May 15, the entire signal and switching system of the New York Central Railroad was put out of operation, followed by the fire in the control tower. Elsewhere, in Sweden a telephone station was burned out, and the storm interfered with telephone, telegraph and cable traffic over most of Europe (Silverman, Cliver 2001; Cliver, Svalgaard 2004; Kappenman 2006).

13 March, 1989 – The Quebec Blackout Storm. This was a severe geomagnetic storm that caused the collapse of the Hydro-Quebec electricity transmission system. It occurred during solar cycle 22. Major Power Failures from Solar Flare. In March 1989, a powerful solar flare set off a major March power blackout in Canada that left six million people without electricity for nine hours. According to NASA, the flare disrupted electrical power transmission and even melted some power transformers in New Jersey. This solar flare was nowhere near the same scale as the Carrington event, NASA scientists said.

The geomagnetic storm causing this event was itself the result of a coronal mass ejection on March 9, 1989. A few days before, on March 6, a very large solar flare also occurred. Three and half days later, on March 13, a severe geomagnetic storm struck Earth (Allen *et al.* 1989). The storm began on Earth with extremely intense auroras at the poles. The burst caused short-wave radio interference, including the disruption of radio signals from Radio Free Europe into Russia.

14 July, 2000 – Bastille Day Events – takes its name from the French national holiday since it occurred the same day on July 14, 2000. This was a

major solar eruption that registered an X5 on the scale of solar flares. The Bastille Day event caused some satellites to short circuit and led to some radio blackouts (Andrews 2001).

29 October – 5 November, 2003. The Ultra-Powerful Halloween Sun Storm. On October 28, 2003, the Sun unleashed a major solar flare. The intense sun storm was so strong it overwhelmed the spacecraft sensor measuring it. The sensor detected X28, already a massive flare, but later analysis found that the flare reached peak strength of about X45, NASA has said.

This super storm event is considered by many scientists to be a wakeup call about the potential threat that has resulted in mobilization of international efforts by scientists from various disciplines to collaborate and pool their research to improve our understanding of this phenomenon (Gopalswamy *et al.* 2005).

18–21 November, 2003. A minor solar storm in October-November 2003 took down the USA Federal Aviation Administration's new Global Positioning System, GPS-based navigation system for 30 hours and damaged electrical systems from Scandinavia to South Africa (Belov *et al.* 2004).

This storm from the Sun disrupted satellite-to-ground communications and Global Positioning System (GPS) navigation signals for about 10 minutes, according to a NASA description. The sun storm was so powerful it actually damaged the solar X-ray imager instrument on the GEOS 13 satellite that snapped its picture, NOAA officials said.

5 December, 2006 – X-Ray Sun Flare for Xmas – when a major X-class solar flare erupted on the Sun on December 5, 2006, it registered a powerful X9 on the space weather scale. This storm from the Sun “disturbed satellite-to-ground communications and Global Positioning Systems (GPS) navigation signals for about 10 minutes”, according to a NASA description.

1.2. Space Weather and its Events

The term space weather refers to adverse conditions and processes on the Sun, in solar wind, or otherwise occurring in space which has the potential to affect the near Earth's environmental – magnetosphere, ionosphere, and thermosphere – and that may affect space-borne or ground-based technological systems (Koskinen *et al.* 2001).

The National Space Weather Program (NSWP) – defines space weather as conditions on the Sun and in the solar 50 kilometers upward from Earth's surface. The most important social and economic aspects of space weather are related to being aware of and possibly avoiding the consequences of space weather events either by system design or by efficient warning and prediction systems allowing for preventive measures to be taken (Koskinen *et al.* 2001).

Several studies have already been performed showing clear evidence of space weather – including adverse effects on the Earth's ionosphere-plasmasphere system (Jakowski *et al.* 1998; Langley, 2000; Jakowski *et al.* 2002; Jakowski *et al.* 2003). Such effects can ultimately cause various types of problems including range errors, or rapid phase and amplitude fluctuations of satellite signals. Aviation and space flight are particularly at risk due to increased radiation and possible navigation-telecommunication problems (Oksanen 1998).

In summary, space environment analysis has always existed. However, the term space weather linking the engineering and the scientific side of the story is more recent. Space weather is an application oriented discipline and addresses the needs of users. On the other hand space weather is application oriented and relies on continuous monitoring, where the results becomes a service product.

A more recent definition of space weather was formulated as “Space weather is the physical and phenomenological state of natural space environments. The associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them; and also at forecasting and nowcasting the possible impacts on technological systems” (Gosling 1993; Baker 2005; Eastwood 2008).

Space weather affects everything either directly or indirectly. There are many aspects and factors as technical systems are becoming more sensitive to the space environment, and will continue to do so in the future due to developments in technology such as miniaturization. Solar-terrestrial physics (STP) science has progressed to a stage where the possibilities for useful space weather models and predictions are expected soon and in some cases already exist (Crosby 2008).

1.3. Definition of Solar Storm Influence on Global Navigation Satellite System Satellite Orbit Elements

There is a lot of activity within and on the Sun because it is composed of gases that are constantly reacting. At various times there are solar events such as solar flares, coronal holes, solar winds (Kahler 1992; Gruntman 1994; Marusek 2007). These activities cause geomagnetic storms that can affect many things on Earth. Some of the more important solar features are explained as sunspots, coronal holes, and aurora (Georgieva, Kirov 2006).

The Sun is an average star, similar to millions of others in the Universe (Lang 2000; Hanslmeier 2002, 2007). It is a prodigious energy machine,

manufacturing about 3.8×10^{23} kiloWatts (or kiloJoules/sec) (Moldwin 2008). In other words, if the total output of the Sun were gathered for one second it would provide the U.S. with enough energy, at its current usage rate, for the next 9,000,000 years (Charbonneau *et al.* 2008). The basic energy source for the Sun is nuclear fusion, which uses the high temperatures and densities within the core to fuse hydrogen, producing energy and creating helium as a byproduct. The core is so dense and the size of the Sun so great that energy released at the center of the Sun takes about 50,000,000 years to make its way to the surface, undergoing countless absorptions and re-emissions in the process. If the Sun were to stop producing energy today, it would take 50,000,000 years for significant effects to be felt at Earth. The Sun has been producing its radiant and thermal energies for the past four or five billion years. It has enough hydrogen to continue producing for another hundred billion years. However, in about ten to twenty billion years the surface of the Sun will begin to expand, enveloping the inner planets (including Earth). At that time, our Sun will be known as a red giant star. If the Sun were more massive, it would collapse and re-ignite as a helium-burning star. Due to its average size, however, the Sun is expected to merely contract into a relatively small, cool star known as a white dwarf (Williams 2004; Phillips 1995).

Solar Storms. Space weather comprises a wide variety of phenomena, which cause different effects. These effects are analogous to meteorological phenomena such as rain, snow, lightning, wind and turbulence. However, the speed, size and scale of space weather effects are not matched in terrestrial weather. Because of this there is no single solution to space weather risk (King 1975; Rind 2002; Pirjola, Kauristie *et al.* 2005; Marusek 2007).

The intensity of these space weather phenomena is much influenced by an 11-year cycle of solar activity (Thomson 1987, 1993; Li 1997; Bounar *et al.* 1997; Lantos and Richard 1998; Shastri 1998; Wilson *et al.* 1998; Hanslemeier *et al.* 1999; Lantos 2000; Verdes *et al.* 2000; Kane 2001; Duhau 2003, Hathaway and Wilson 2004; Kane 2008; Dabas and Sharma 2010). This is traditionally measured by counting the numbers of sunspots – spots on the face of the Sun that appear dark because they are cooler than the surrounding regions (Livingston, Penn 2009). At the maximum of the solar cycle, violet events are common on the Sun. When those events eject solar matter and energy towards the Earth they produce space weather phenomena, such as intense magnetic and radiation storms. At the minimum of the cycle the Sun is usually, but not always, much quieter, so the Earth is more exposed to the steady flows of matter and energy from the Polar Regions of the Sun and from outside the Solar System. These produce smaller, but still dangerous, space weather effects on Earth, including long-lasting increases in radiation and recurrent magnetic storms.

Solar storms consist of three major components: solar flares, solar proton events (SPEs) and coronal mass ejection (CMEs) (Zhang *et al.* 2003; Marusek 2007). CMEs can interact with Earth's magnetic field to produce geomagnetic storms. Not all solar storms produce all three elements but the largest solar storms tend to. Table 1.1 lists the arrival time sequence for solar storm elements (Marusek 2007).

Table 1.1. Time Sequence of Solar Storm Events

Components	Arrival Time	Effect Duration
Solar Flares	Instantaneous	1–2 hours
Solar Proton Event	15 minutes to a few hours	Days
Coronal Mass Ejection	2 or 4 days	Days

The sun undergoes a cyclical (~22 year) pattern of magnetic pole reversal, which is also observable in the frequency of sunspot activity. This pattern is comprised of two ~ 11 years solar cycle phases (Friis–Christensen, Lassen 1991; Webb, Howard 1994; Kodera, Kuroda 2002). In the first phase, the Sun's magnetic poles reverse polarity. In the second phase, the Sun reverses the magnetic polarity again returning the poles back to their original polarity. Solar storm activity is strongly phase correlated and also very dependent on the position within the solar cycle (Marusek 2007).

Sunspots are the sites of origin for great solar storms (McIntosh 1990). The sun spins on its axis. As seen from Earth, the average rotation period of the Sun averages 27 days. Great sunspot groups can stay active for several solar revolutions creating a cyclical ~27 day pattern of solar storms (Neugebauer *et al.* 2000; Haneychuk *et al.* 2003; Kane 2003).

Solar Flares. Solar flares are magnetically driven explosions on the surface of the Sun (Moore *et al.* 2001, 2007). Approximately 8 minutes after a solar flare occurs on the surface of the Sun, powerful bursts of electromagnetic radiation in the form of X-ray, extremes ultraviolet rays, gamma ray radiation and radio bursts arrive at Earth (Jansen, Pirjola 2004; Echer *et al.* 2005). The ultraviolet rays heat the upper atmosphere, which causes the outer atmospheric shell to expand. The X-rays strip electrons from the atoms in the ionosphere producing a sudden increase in total electron content.

Solar flares produce satellite communications interference, radar interference, shortwave radio fades and blackouts and atmospheric drag on satellites producing an unplanned change in orbit (Marusek 2007).

Scientists classify solar flares according to their brightness at the X-ray wavelengths. They group flares into 3 categories (X-class, M-class and C-class) (Lang 2001). Referring to table 1.2, C-class flares are very small and produce few noticeable effects on Earth. M-class flares are medium-sized and can cause

brief radio blackouts in the Polar Regions. X-class flares are major events that can trigger worldwide radio blackouts and radiation storms in the upper atmosphere (Echer *et al.* 2005; Marusek 2007).

Table 1.2. Classification of Solar Flare Intensity

Class	Peak Flux Watts/meter ² (100–800 picometer X-rays near Earth)	Class	Peak Flux Watts/meter ² (100–800 picometer X-rays near Earth)
M1	$0.1 \times 10^{-4} \text{ W/m}^2$	X1	$1.0 \times 10^{-4} \text{ W/m}^2$
M2	$0.2 \times 10^{-4} \text{ W/m}^2$	X2	$2.0 \times 10^{-4} \text{ W/m}^2$
M3	$0.3 \times 10^{-4} \text{ W/m}^2$	X3	$3.0 \times 10^{-4} \text{ W/m}^2$
M4	$0.4 \times 10^{-4} \text{ W/m}^2$	X4	$4.0 \times 10^{-4} \text{ W/m}^2$
M5	$0.5 \times 10^{-4} \text{ W/m}^2$	X5	$5.0 \times 10^{-4} \text{ W/m}^2$
M6	$0.6 \times 10^{-4} \text{ W/m}^2$	X6	$6.0 \times 10^{-4} \text{ W/m}^2$
M7	$0.7 \times 10^{-4} \text{ W/m}^2$	X7	$7.0 \times 10^{-4} \text{ W/m}^2$
M8	$0.8 \times 10^{-4} \text{ W/m}^2$	X8	$8.0 \times 10^{-4} \text{ W/m}^2$
M9	$0.9 \times 10^{-4} \text{ W/m}^2$	X9	$9.0 \times 10^{-4} \text{ W/m}^2$

The largest observed solar flare was the Carrington light flare of September 1, 1859. The largest measured solar flare occurred on November 4, 2003 and was rated as an X45.

Solar Proton Events (SPE). Sun produce high-energy solar cosmic rays (protons and ions) in Solar Proton Events (SPEs). These particles generally have energies in the range of 10 MeV to 100 MeV (Vacaresse *et al.* 1999; Miroshnichenko *et al.* 2001). Very energetic SPE events are also capable of generating near-relativistic protons in the order of 20 GeV^{-4} . Table 1.3 gives the arrival time of the protons based on energy level after the solar flare first become visible on the Earth. In general, SPEs take around an hour to reach Earth (Marusek 2007).

Table 1.3. Velocity of Proton

Energy	Velocity (speed of light)	Arrival Time
1 MeV	0.046 c	2.9 hours
10 MeV	0.145 c	49 minutes
100 MeV	0.429 c	11.1 minutes
1 GeV	0.875 c	1.2 minutes

Solar proton events produce satellite disorientation, spacecraft electronics damage, spacecraft solar panel degradation, extreme radiation hazard to astronauts, launch payload failure, high altitude aircraft radiation, shortwave radio fade and disruption in Polar Regions, ozone layer depletion.

Coronal Mass Ejections (CMEs).). The outer solar atmosphere, the corona, is structured by strong magnetic fields. Where these fields are closed, often above sunspot groups, the confined solar atmosphere can suddenly and violently release bubbles or tongues of gas and magnetic fields called coronal mass ejections (Antiochos *et al.* 1999; Low 2001; Marusek 2007). A large CME can contain 10^{16} grams (a billion tons) of matter that can be accelerated to several million miles per hour in a spectacular explosion (Cane 2000; Webb 2000, 2002; Nindos *et al.* 2008). Solar material streaks out through the interplanetary medium, impacting any planet or spacecraft in its path. CMEs are sometimes associated with flares but usually occur independently.

All of these forms of solar activity are believed to be driven by energy released from the solar magnetic field (Moore *et al.* 2008; Antiochos *et al.* 2009). How this energy releases occurs, and the relationship between different types of solar activity, is one of the many puzzles facing solar physicists today. The amount of solar activity on the Sun is not constant, and is closely related to the typical number of sunspots that are visible (Tsiropoula 2003). The number of sunspots and the levels of solar activity vary with an 11-year period known as the solar cycle (Friis – Christensen, Lassen 1991).

The NOAA Space Weather Scales. Solar storms vary in size and impact on GNSS and Earth. Research now suggests there is a different class of space weather effects on signals: solar radio burst. NOAA deliver space weather impacts on satellite navigation, it is call NOAA Space Weather Scales. The NOAA space weather scales can be grouped into tree different parts:

1. Geomagnetic storms
2. Solar radiation storms
3. Radio blackouts.

Geomagnetic Storms: The Sun emits a low-density wind of ionised matter (plasma) that fills the Solar System. The Earth is normally shielded from this 'solar wind' by its magnetosphere (Baker 1996). However, the solar wind is sometimes enhanced by coronal mass ejections (CMEs) that are high-speed bursts of denser material ejected from the Sun when the magnetic fields in the Sun's atmosphere become unstable (Cane 2000; Webb 2000, 2002; Moore *et al.* 2008). They are most common near solar maximum. CMEs contain strong south-pointing magnetic fields (ie opposite to the Earth's magnetic field) and can overcome the magnetospheric shielding, allowing the CME's energy to reach the Earth. This intensifies electric currents that flow within the magnetosphere, causing rapid changes in the Earth's magnetic field (hence "magnetic storm"). These changes can disrupt the operation of power grids, pipelines, railway signalling, magnetic surveying and drilling for oil and gas.

These electric currents also produce the aurora borealis or northern lights (Langley 2000; Boteler 2003; Marusek 2007). The electrons that form part of these currents interact with oxygen atoms in the upper atmosphere to produce the bright red and green glows seen in these spectacular natural phenomena.

Magnetic storms also heat the upper atmosphere, changing its density and composition and disrupting radio communications that pass through this region (Crosby 2008; Wilkinson 2012).

Disturbances in the geomagnetic field are caused by gusts in the solar wind that blows by Earth (Piddington 1960; Poppe 2000; Gibson *et al.* 2009). Typical effects from geomagnetic storms include degradation of HF radio transmissions, satellite navigation degradation, and disruption of low frequency radio navigation systems. Geomagnetic storms can also disrupt electrical power grids, and GPS operations are susceptible to these power outages (Jansen, Pirjolia 2004; Baker 2005; Marusek 2007; Hapgood 2011). Additionally, geomagnetic storms weaken the ability of the Earth's magnetic field to deflect incoming charged particles.

Geomagnetic storms are divided into five categories (table 1.4), G1–G5 where the last has the most severe effects (Yakovchouk *et al.* 2009).

Table 1.4. Geomagnetic Storm severity categories affecting satellite navigation

Category		Effects	Number of affected days per 11 year Sun Cycle
Scale	Severity		
G5	Extreme	Satellite navigation and positioning degraded for some days	4 days
G4	Severe	Satellite navigation and positioning degraded for some hours	60 days
G3	Strong	Intermittent satellite navigation and positioning problems	130 days
G2	Moderate	Predicted satellite orbits influenced by drag effects	360 days
G1	Minor	Satellite navigation and positioning unaffected	900 days

Solar Radiation Storms: Elevated levels of radiation that occur when the numbers of energetic particles increase (Koskinen 2001; Marusek 2007). Typical effects from solar radiation storms include degradation of satellite tracking and power systems (table 1.5). Induced positional errors to GPS are also possible.

Table 1.5. Five categories of Solar Radiation Storms

Category		Effects	Number of affected days per 11 year Sun Cycle
Scale	Severity		
S5	Extreme	Satellite navigation and positioning mainly unaffected	Less than 1 day
S4	Severe		3 days
S3	Strong		10 days
S2	Moderate		25 days
S1	Minor		50 days

Radio Blackouts: Disturbances of the ionosphere caused by X-rays emissions from the sun. Low frequency navigation signals may experience outages on the sunlit side of the Earth for hours, causing loss in positioning. Extreme events can cause increased errors in positioning for hours on the sunlit side of Earth, which may spread into the night side (table 1.6).

Table 1.6. Five categories of Radio Blackouts

Category		Effects	Number of affected days per 11 year Sun Cycle
Scale	Severity		
R5	Extreme	Satellite navigation and positioning errors for several hours on the sunlit side of the earth, possibly spreading into the night side	Less than 1 day
R4	Severe	Minor disruptions to satellite navigation and positioning on sunlit side of Earth	8 days
R3	Strong	No significant effects on satellite navigation and positioning	140 days
R2	Moderate	No significant effects on satellite navigation and positioning	300 days
R1	Minor	No significant effects on satellite navigation and positioning	950 days

1.4. Principals of Ground Positioning by Global Navigation Satellite System

Global Positioning System satellite signals are affected when solar storms cause sudden variations in the density of the ionosphere, causing the GPS signals to scintillate. Solar storms can add small delays to the GPS satellite signals

impacting accuracy. Solar storms will also cause signal fades that will make it difficult to gain and maintain satellite signal lock. The major risk is the potential to lose the satellite navigation signal completely. It is expected that disturbed space weather conditions will become much more common in the period from 2012 to 2015 due to increasing solar activity. Therefore it is likely users will experience a loss of signal more often. In such cases, major position errors (Braasch, Van Graas 1991; Seeber 1993; Qui, 1993; Klobuchar *et al.* 1995; Kaplan 1996; Kunches 1997; Knight, Finn 1998; Jefferson *et al.* 2000; Neilan *et al.* 2000; Ray 2000; Skone 1998, 2001; Skone *et al.* 2001) may be expected to arise, perhaps comparable to those caused by the transmission of competing radio signals, known as jamming. For example, a recent jamming test in the UK showed position errors of up to 20 km.

GPS receivers calculate their location by analysing from a constellation of satellites, but those signals can be delayed or distorted. Space weather phenomena, such as solar flares and geomagnetic storms, can result in errors in position and navigation and degraded or loss of signals. Such solar activity can affect the accuracy of single-frequency GPS receivers, while dual-frequency GPS receivers can better adjust to a disturbed ionosphere, but still experience some difficulty.

GPS is used by millions of people around the world. Many GPS users will experience little or no effect during geomagnetic storms, but those requiring precise GPS measurements have a great need for NOAA/SWPC alerts and warnings of problematic space weather conditions. Most vulnerable applications include: surveying companies using GPS measurements for land surveying, topographic work, and boundary analysis; deep-sea drilling operations; land drilling and mining; and various defence-related activities.

Position computation depends on knowing the positions of the used satellites. Satellite positions are computed from parameters that describe their orbits. These parameters are in turn predictive, and can be replaced by precise parameters post-processed from tracking (IGS o.l.) However, the average surveyor is interested in (and prepared to pay for) real time results, which obviously precludes the use of these precise ephemerides.

Most production uses of GNSS surveying systems, whether for positioning, setting out or machine guidance, rely on the principles of differential positioning, where differencing techniques are used to eliminate errors. Indeed, it can (and has) been argued that these differencing techniques will safely remove any residual errors there may be in the predictive orbit parameter sets transmitted by the satellites.

On the other hand, having to operate together with some form of reference system – be it a local reference station or a virtual reference station system – can only be considered to be an “expensive necessity”. Publicly stated objectives for

the future are to improve the single point positioning capabilities significantly, so that a larger proportion of survey users will no longer need to operate against reference stations. (GALILEO aims to provide one metre accuracy for single point positioning.) Reducing to single point positioning starts to remove the rather more concealed advantage of differential positioning obtained from differencing techniques. Therefore, errors in satellite orbit parameters can suddenly start to be significantly interesting again. Also, it has to be remembered that orbit parameters are only uploaded to the satellites "every so often". (Looking at the literature, it seems that parameters are updated every four hours or so, so in the worst case, a user could be operating on incorrect orbit parameters for up to four hours before the new upload takes place.)

Meanwhile, the media report that the next solar-high-activity cycle is predicted (confidence in the high nineties percentile) to be very significantly stronger than in recent cycles. 30% to 50% stronger has been mentioned. The storming effects associated with high solar activity are able to physically "push" satellites off course, rendering their predictive orbital parameters in error. It can be argued that if all satellites are all pushed off course in the same direction by the same amount, then the effect on the differentially produced ground position will disappear due to differencing. If however differencing is not involved, then the question becomes what effect such orbital course disturbances have on the ground receiver's position.

1.5. Influence of Earth's Shadow on Global Navigation Satellite System

Once the satellites go into the shadow, the radiation pressure vanishes. This effect introduces errors in the satellite dynamics due to the difficulty of properly modelling the solar radiation pressure. This effect introduces errors in the satellite dynamics due to the difficulty of properly modelling the solar radiation pressure. On the other hand, the satellite solar sensor loses sight of the Sun and the attitude control (trying to keep the panels facing the Sun) is degraded. The yaw attitude of GPS satellites is essentially random during an eclipse and for up to 30 minutes past exiting from shadow. Each GPS satellite has two eclipse seasons per year, each lasting for about seven weeks (Mervat 1995). There are two types of Sun eclipse that cause a geostationary satellite to be in shadow. The most common one is caused by the Earth blocking the sunlight and happens near equinoxes. Earth caused eclipses can continue for up to 45 days around equinox with the satellite being in shadow for up to 70 minutes each day.

Positioning and navigation using satellites remains a process of three-dimensional triangulation, where it is necessary to know or measure the

positions of sufficient satellites together with the distance to those satellites from the ground observer. Providing knowledge of the satellites' instantaneous position on orbit is the responsibility of the Space Control Segment, in the sense that appropriate parameters are uploaded to the satellites for subsequent broadcasting to terrestrial receivers. Thus, those receivers need to be equipped with the firmware necessary to decode the incoming parameters and then to carry out the necessary computations.

Measuring the distance to the satellites is done indirectly, by recording the time of arrival of discrete elements of the incoming signal, which also describe the time of their departure from the satellites. These time measurements are made using timepieces which themselves carry some error with them. The error in the satellite timepieces is relatively predictable and the satellites broadcast parameters describing them. The timing error in the terrestrial receiver is meanwhile unknown, and, since the necessary timepiece is normally somewhat less precise than those in space, cannot be easily predicted. Therefore, sufficient satellites are observed simultaneously to be able to develop the instantaneous clock error as one of the positioning unknowns.

All of the above therefore depends on a series of predictions for each satellite – predictions of the satellites orbital movement, and predictions of the behaviour of the satellites' clocks. It is the behaviour of the satellites' orbits, which is of interest here.

As already indicated the Space Control Segment prepares the necessary orbital predictions and uploads them to the satellites at regular intervals. Clearly, at the time of upload, the orbital parameters can be expected to be relatively accurate. With the passage of time towards the next update, however, the accuracy of the predictions can be expected to decay to some degree. Nevertheless, this decay in orbit prediction accuracy is of no concern to the average navigator and recreation user. Indeed, it may normally be of little importance to all but the most advanced users seeking the best possible accuracy.

The reasons for the decay in orbit prediction with time can be summarised as being a combination of residual errors in the modelling of the geo-potential surface at orbit altitude, coupled with the effects of various forms of radiation that are impinging on the satellite. Of the latter, the various forms of solar radiation perhaps dominate. However, the actual cause of the decay is of less concern to the high precision user. The degree to which the user's positional accuracy is degraded is much more of interest. Further, the high precision user is naturally interested in developing procedures to avoid decay where possible.

Serious research and monitoring of solar activity is very well established because modern society's infrastructure has certain serious vulnerabilities to solar storming. Over recent years, space weather forecasting and warning

systems have become available, and records of activity are in the public domain. Thus, it is not difficult to determine from recent records whether and when solar storms have impacted on the Earth.

Meanwhile, aside from and yet complementary to the activities of the Space Control Segments, the International GNSS Service publishes precise a posteriori orbital information based on a worldwide geodetic tracking network. Certain comparisons can thus be made.

In particular, it might be logically assumed that orbit disturbance due to solar pressures would not take place when the satellite is in shadow – in eclipse. Here, of course, the satellite can find itself in the Moon's shadow and/or the Earth's shadow. Either way, it is suggested that some shielding from solar radiation and wind effects might be expected. The question is – how much difference can this make to precise terrestrial positioning. Further, if the positioning accuracy is significantly degraded, is it now becoming timely for precision users to follow space weather forecasting services, and to avoid measuring their positions at times of high risk.

Additionally, it must be remembered that the satellites are effectively powered by sunlight, supported by batteries. Once a satellite disappears into shadow, then the systems for orienting solar panels towards the Sun become, perhaps, slightly confused and start to hunt. At the same time, orienting the satellites in their correct attitude towards the Earth is also to a degree dependent on input from solar panel array orientation towards the Sun. Thus, while in eclipse, not only is the satellite draining power while it continues to hunt for the Sun, it may also be drifting slightly out of its correct orientation, thus introducing potential errors due to offsets between the satellite's centre of gravity and the electrical centres of its various transmitting antenna.

Another aspect of the argument is that investigating positioning decay caused by using or not using eclipsed satellites will provide a relatively simple indication of the seriousness or otherwise of these concerns.

The situation is perhaps further complicated by the consequences of satellites passing through eclipse. Here, if the Sun decides to storm, then all satellites visible to the Sun can be assumed to be similarly affected. Satellites in partial eclipse might be less affected, while those actually in full umbra would logically be completely unaffected. On the other hand, GNSS is a 24 hour system, and there is nothing to say, at least at present, that surveyors will only use satellites when they are illuminated by the Sun. Therefore, the question arises as to what effect there might be on a ground receiver's position if not all satellites are pushed off course. Is this consequence significant, in terms of the repeatabilities expected now and in the medium 10 to 20 year future, and given an already predicted high activity solar high?

1.6. Conclusions of Chapter 1 and Formulation of the Research Tasks

The following conclusions are drawn from study of the scientific literature:

1. The risk of extreme space weather from solar storms is not a totally new or unknown phenomenon. Our understanding of this risk is based on prior events in last 150 years, primarily the 1859 Carrington Event, 1989 Quebec blackout and the super storms in 2003. The heightened attention at this time is due to a prediction of an extreme solar cycle maximum around 2012-15. If the 1989 Quebec blackout and the 1859 Carrington Event are benchmarks for adverse outcomes from similar solar storm events in the future, the consequences could be greatly magnified due to our growing dependence on technology.
2. Solar storms consist of three major components: solar flares, solar proton events (SPEs) and coronal mass ejection (CMEs). CMEs can interact with Earth's magnetic field to produce geomagnetic storms. Not all solar storms produce all three elements but the largest solar storms tend to.
3. It is expected that disturbed space weather conditions will become much more common in the period from 2012 to 2015 due to increasing solar activity. Therefore it is likely users will experience a loss of signal more often. In such cases, major position errors may be expected to arise, perhaps comparable to those caused by the transmission of competing radio signals, known as jamming.
4. When the Sun is stormy, then all satellites visible to the Sun can be assumed to be similarly affected. Satellites in partial eclipse might be less affected, while those actually in full umbra would logically be completely unaffected. On the other hand, GNSS is a 24-hour system, and there is nothing to say, at least at present, that surveyors will only use satellites when they are illuminated by the Sun.

Evaluation of the scientific literature analysis highlighted the problems and taking into account the objective work, it would be appropriate to address the following challenges:

1. To examine the influence of solar activity on GNSS satellites' orbits, and as a consequence on the accuracy of ground positions.
2. The examination should include consideration of Earth's shadowing (i.e. satellites in eclipse) under solar storming conditions.

Theory and Methods to Evaluate Global Navigation Satellite System Satellite and Receiver Positions

The purpose of this chapter is to explain the processes and formulas required to obtain GNSS satellite and receiver positions, as well as demonstrating the idea of finding out which satellites are in eclipse. The chapter provides a review of the necessary orbital theory to introduce the reader into the methods of computing satellites' and the Sun's ephemerides.

2.1. Introductory Remarks

The observational data that was used throughout these studies were presented as text files in the well-known RINEX format (Gurtner 2002, 2005, 2007). Inevitably, there were some differences in the RINEX version that had been implemented at the various stations. These differences had at times serious consequences from the programming viewpoint.

At the same time, it is further underlined that these data files were in text form. In other words, they were in readable form, rather than in some form of unreadable machine coded language. Therefore, much of the programming that

was required consisted of disassembling and assembling text data into forms that would be meaningful to the programs that would subsequently process them.

Put another way, the experience of preparing these programs showed that:

- Program segments to fill algorithmic formulæ is relatively straightforward;
- Program segments to dismantle text strings and convert them into usable numbers - without losing precision or sign – is a rather more complex affair.

With this in mind, it was decided to use the Quick Basic programming system with its associated FBI program editor. This decision was mostly based on the fact that Basic is known to be particularly suited to text string handling.

Regarding computer programing strategies, the approach throughout has been to prepare and test short programs that would advance a single step through the processes described above. In this way, these short programs were relatively simple to prepare and test and then put into production.

2.2. Conversion of Civil Date to GPS Week and Seconds-in-Week

The civil date is expressed by integer values for the year Y , month M , and day D , and a real value for the time in hours Universal Time (UT) (Hofmann-Wellenhopf, Lichtenegger, Collins 2001; Skeivalas 2004). Then:

$$JD = INT[365.25y] + INT[30.6001(m+1)] + D + UT / 24 + 1720981.5. \quad (2.1)$$

is the conversion into Julian date where INT indicates an operator extracting the integer part of a real number (and truncating the fraction part) and y, m are given by:

$$\begin{array}{lll} y = Y - 1 & \text{and} & m = M + 12 \quad \text{if} \quad M \leq 2 \\ y = Y & & m = M \quad \text{if} \quad M > 2 \end{array}$$

Knowing the Julian Date, the GPS Week Number is calculated as follows:

$$WEEK = INT[(JD - 2444244.5) / 7]. \quad (2.2)$$

This procedures the value of WEEK counting from 6th January 1980. However, particularly for GPS only 1024 values of WEEK are allowed, to get correct value of week it is necessary to begin subtracting 1024 from the above value until a value is obtains that is less than 1024.

Additionally, JD is used to calculate which day of the week (N) the given Civil Date has fallen on (Hofmann-Wellenhof, Lichtenegger, Collins 2001).

$$N = \text{modulo} \left[7 \left\{ (JD + 0.5) / 7 - \text{INT} \left[(JD + 0.5) / 7 \right] \right\} \right]. \quad (2.3)$$

where N=0 denotes Monday; N=1 means Tuesday, etc.

The algorithm is rewritten in *FBIde* program, which is located in Annex A.

2.3. Navigation Message

This program reads RINEX Navigation message files and does the following (Annex B):

- Removes repeated navigation message sets for individual satellites
- Extracts the individual navigation message parameters into a format, which makes these data more easily available in the processes of file handling and in later programs.

It was important to understand that there are small differences in the way different manufacturers' programs prepare RINEX files.

Examining navigation files showed the following:

- As expected the detailed navigation messages for individual satellites for a specific TOE (time of ephemeris) as recorded at different stations here exactly the same.
- As 24-hour data sets were used it was found unnecessary to use navigation messages recorded at each station, because the data set from one station contained enough data to support observations at all stations.

2.4. Computation of Satellite Position

The application of operational satellite methods depends substantially on knowing the satellite orbits. For single receiver positioning, a receiver's position is highly correlated with the errors in the satellites' orbit positions. In the case of baselines, relative orbital errors are approximately equal to relative baseline errors.

At the same time, it is clear that the same coordinate system must be used for receivers and satellites. In the context of this project, this principle is extended to include that the Sun's coordinates must also be in the same system.

Further, it is also clear that the phrase “coordinate system” as applied here must inevitably include the concept of a common time system.

Table 2.1. Uncertainties of ephemerides

Ephemerides	Uncertainty	Remark
Almanac	Some kilometers	Depending on the age of data
Broadcast ephemerides	~ 1 m	Or even better
Precise ephemerides	0.05–0.20 m	Depending on the latency

Three sets of data are available to determine position and velocity vectors of the satellites in a terrestrial reference frame at any instant: almanac data, broadcast ephemerides, and precise ephemerides (table 2.1). The data differ in accuracy and are available either in real time or with some delay after the fact.

2.4.1. Broadcast Ephemerides

The satellites “know” their position and transmit this information (the broadcast ephemeris) to the users. The GPS signal contains information about the position of the GPS satellites, the broadcast ephemeris, in the broadcast (navigation) message (Peeters 1999). The broadcast ephemerides are based on observations at the monitor stations of the respective control segment. The most recent of these data are used to compute reference orbits for the satellites. Additional tracking data are entered into a Kalman filter and the improved orbits are used for extrapolation into the short-term future. The control segment is responsible for the computation of these predictive ephemerides and their subsequent upload to the satellites.

The broadcast ephemerides are part of the satellite message. Essentially, the ephemerides contain records with general information, records with orbital information, and records with information on the satellite clock. The orbital information is provided in the form of Keplerian parameters (Ažusienis *et al.* 2003; Leick 2004; Skeivalas 2004, 2008; Hofmann–Wellenhof *et al.* 2001, 2008) together with their temporal variations (e.g., for GPS) or position and velocity vectors at equidistant epochs (e.g., for GLONASS). The information on the satellite clock is in most cases given in the form of coefficients to model the clock offset from system time by means of polynomials. The location of the satellites can be used to compute the position in Cartesian coordinates in the WGS84 coordinate frame at any given time.

In principle, to define the orbit of a satellite, a minimum set of six time-tagged numbers is required. These numbers define an ellipse, orient it about the Earth, and place the satellite on the ellipse at a particular time. In the Keplerian

model, satellites orbit in an ellipse of constant shape and orientation (Langley 1991; Hofmann-Wellenhof *et al.* 2001).

Table 2.2 gives the definition of all the orbital parameters used to define the orbits of the GPS satellites. The parameters in the block of orbital information are the reference epoch, six parameters to describe a Kepler ellipse at the reference epoch, three secular correction terms, and six periodic correction terms. The nine correction terms allow for perturbation effects due to the non-sphericity of the Earth, the direct tidal effect, and the solar radiation pressure. The ephemerides are regularly updated, as already explained, and should only be used during a specified time interval (Leick 2003; Skeivalas 2004, 2008).

Table 2.2. Ephemeris parameters in the navigation message

Parameter	Explanation
$\sqrt{a}$	Square root of the semi major axis
e	Eccentricity
i_0	Inclination angle at the reference time
Ω_0	Longitude of the ascending node at the beginning of the GPS week
ω	Argument of perigee
M_0	Mean anomaly at the reference time
Δn	Correction to the mean motion computed using $\sqrt{a}$
$i - \text{dot}$	The rate of change of the inclination with time
$\Omega - \text{dot}$	The rate of change of the right ascension of the ascending node with time
C_{uc}, C_{us}	Amplitude of correction terms for the computed argument of latitude
C_{re}, C_{rs}	Amplitude of correction terms for the computed orbit radius
C_{ie}, C_{is}	Amplitude of correction terms for the computed inclination angle
t_{oe}	Ephemeris reference time

The satellite position Cartesian coordinates at a certain time are calculated from the Keplerian broadcast ephemeris elements by applying a series of formulas. This process is shown below. In order to compute the satellite position at the observation epoch t , the following quantities, apart from the parameters a and e , are needed and used as described in ICD-200:

Gravitation constant for WGS84 (Featherstone 1996; Featherstone *et al.* 1997; Li *et al.* 2001):

$$\mu = 3.986005 \times 10^{14} \text{ meters}^3 \text{ per second}^2$$

Earth's rotation rate for WGS84 (Malys *et al.* 1994; Skeivalas 2008):

$$\dot{\Omega}_e = 7.2921151467 \times 10^{-5} \text{ radians per second}$$

The semi-major axis length of the orbital ellipse comes immediately from:

$$a = \left(\sqrt{a} \right)^2. \quad (2.4)$$

According to Kepler's Third Law, the mean motion n_0 – rad/s – angular velocity – of a satellite is given by:

$$n_0 = \sqrt{\frac{\mu}{a^3}}. \quad (2.5)$$

This is the theoretical value of the satellite's motion, and has to be corrected by the Δn parameter obtained from satellite message (Skeivalas 2008):

$$n = n_0 + \Delta n = \sqrt{\frac{\mu}{a^3}} + \Delta n. \quad (2.6)$$

Time from ephemeris reference epoch:

$$t_k = t - t_{oe}. \quad (2.7)$$

t is GPS system time measured in seconds of week from week start, at time of transmission, i.e., GPS time corrected for transit time (range/speed of light). Furthermore, t_k shall be the actual time difference between the time t and the epoch time t_{oe} , and must account for beginning or end of week crossovers. That is, if t_k is greater than 302,400, subtract 604,800 from t_k . If t_k is less than -302,400 seconds, add 604,800 seconds to t_k .

It is now possible to correct the satellites' Mean, Eccentric and True Anomalies up to the epoch of observation concerned (Skeivalas 2008):

$$M_k = M_0 + nt_{oe}. \quad (2.8)$$

Kepler's equation for eccentric anomaly (Skeivals 2003, 2008):

$$E_k = M_k + e \sin E_k. \quad (2.9)$$

True anomaly:

$$\begin{aligned} v_k &= \tan^{-1} \left\{ \frac{\sin v_k}{\cos v_k} \right\} = \tan^{-1} \left\{ \frac{\sqrt{1-e^2} \sin E_k / (1-e \cos E_k)}{(\cos E_k - 1) / (1-e \cos E_k)} \right\} = \\ &= \tan^{-1} \frac{\sqrt{1-e^2} \sin E_k}{\cos E_k - 1}. \end{aligned} \quad (2.10)$$

The value of E_k as determined in equation (2.9) depends on E_k itself. This is solved by iteration, where in the first attempt, $\sin M_k$ is used on the right of the equals sign. The resulting first value of E_k is then used in the form $\sin E_k$ to

evaluate the equation again. This process is repeated until the resulting value of E_k does not alter further.

Eccentricity anomaly:

$$E_k = \cos^{-1} \left\{ \frac{e + \cos v_k}{1 + e \cos v_k} \right\}. \quad (2.11)$$

The angular distance around the orbit from the Ascending Node crossing the Equatorial Plane going north to the satellite's position Φ_k – is then obtained by adding the True Anomaly v_k and Argument of Perigee ω .

Argument of latitude:

$$\Phi_k = v_k + \omega. \quad (2.12)$$

The Argument of Perigee, orbit radius and orbit inclination are corrected up to the epoch of observation by producing respectively $\delta u_k, \delta r_k, \delta i_k$. Second harmonic perturbations:

$$\left. \begin{aligned} \delta u_k &= C_{uc} \sin 2\Phi_k + C_{us} \cos 2\Phi_k \\ \delta r_k &= C_{rc} \cos 2\Phi_k + C_{rs} \sin 2\Phi_k \\ \delta i_k &= C_{ic} \cos 2\Phi_k + C_{is} \sin 2\Phi_k \end{aligned} \right\}. \quad (2.13)$$

Corrected argument of latitude:

$$u_k = \Phi_k + \delta u_k. \quad (2.14)$$

While the orbit radius and inclination at epoch, including corrections, are obtained from. Corrected radius:

$$r_k = a(1 - e \cos E_k) + \delta r_k. \quad (2.15)$$

Corrected inclination:

$$i_k = i_0 + \delta i_k + (i - \dot{i})t_k. \quad (2.16)$$

So far, the satellite's position has been described with respect to how far it has moved around its orbit since it crossed the Equatorial plane going north. The whole is now transformed so that the final resulting satellite position is given in the required three-dimensional Earth-centred Cartesian co-ordinate system. Two intermediate parameters - x'_k and y'_k - are first evaluated. Positions in orbital plane:

$$\left. \begin{aligned} x'_k &= r_k \cos u_k \\ y'_k &= r_k \sin u_k \end{aligned} \right\}. \quad (2.17)$$

Now, Ω_k comes out as the total angular distance in the Equatorial plane from the free-dimensional co-ordinate x-axis – in other words the satellite's longitude Corrected longitude of ascending node:

$$\Omega_k = \Omega_0 + (\dot{\Omega} - \dot{\Omega}_e)t_k - \dot{\Omega}_e t_{oe}. \quad (2.18)$$

Earth-fixed coordinates (Skeivalas 2008):

$$\left. \begin{aligned} X_k &= x'_k \cos \Omega_k - y'_k \cos i_k \sin \Omega_k \\ Y_k &= x'_k \sin \Omega_k + y'_k \cos i_k \cos \Omega_k \\ Z_k &= y'_k \sin i_k \end{aligned} \right\}. \quad (2.19)$$

Correct application of the above algorithms demands a clear understanding of the meaning of the different orbital parameters that are used. Specifically, certain of these parameters (the anomalies) cannot have a negative value according to the way that the parameters are defined. On the other hand, “blind application” of these algorithms often evaluated them with negative values. This was because of incorrect interpretation of inverse trigonometric functions (arcsin, arcos, arctan). For confirmation, resulting satellite coordinates were regularly compared with precise ephemerides to check that differences were acceptable, i.e. within reasonable limits, looking at smoothness of change from epoch to epoch in each of the three positional coordinates.

2.4.2 Comparison of Broadcast and Precise Ephemerides

The aim of this program is to combine broadcast ephemeris coordinates at epoch (as computed in the previous program) with precise ephemeris coordinates into a single file. The resulting file contains:

- the satellite number;
- the epoch in terms of second of week (SoW);
- the broadcast coordinates and satellite clock error;
- the precise ephemeris coordinates and satellite clock error;
- differences between broadcast and precise.

2.5. Computation of Satellite in Earth Shadow

The overall aim of the eclipse study is to determine whether the fact of a satellite being in eclipse affects the quality of positioning when that satellite is in use. This question is particularly interesting under solar storming conditions, when logic would suggest that eclipsed satellites are shielded from the Sun's effects, while those satellites not in eclipse may well have their orbits diverted, thereby possibly contaminating position determinations on or near the Earth's surface.

To study these problems, it is of course first necessary to determine when satellites are in eclipse. Further, to establish whether eclipsed satellites affect GNSS system performance, it is also necessary to be able to determine when eclipsed satellites are actually observable over the horizon from a given surface location.

There are plenty of available proprietary satellite availability programs which will calculate and display which satellites are visible for a given surface position and a given elevation mask angle. However, modifying these programs to include eclipse timings is not considered to be a realistic option, because of these programs' proprietary nature. Therefore, relatively simple software has been developed which both lists satellite visibility over the horizon and also notes which if any of these visible satellites is in eclipse. The results are not intended to be ultra accurate, and are more intended for use as an indicator to events which need more detailed studies – and probably their own more detailed programs (Annex D).

2.6. To Determine which Satellites are in Earth Shadow

Determining whether a satellite is or is not in eclipse requires that the Earth's shadow at the altitude of the satellite orbits is defined. This in turn means that the Sun's apparent position needs to be determined in an Earth-based coordinate system. A number of assumptions are made, not least about the circularity and radius of the Earth's orbit around the Sun, as well as treating the Earth itself as a sphere instead of an ellipsoid.

In essence, discovering whether a satellite is or is not in eclipse involves finding out the latitude and the longitude of the meridian at which – at a given epoch – the sun is directly overhead. Adding 180 degrees or reversing signs gives the point on the opposite side of the globe. Then adding the satellite orbit altitude to the Earth's radius gives three-dimensional coordinates of the point on the line directly between Sun centre, Earth centre and satellite orbit on the

shadow side. Thereafter, simple Pythagorean calculation can compare distance to satellite with the shadow radius.

The processes involved are also readily described in the following table 2.3.

Table 2.3. Processes of determining satellites in eclipse

Solar Polynomials	1. Calculate the latitude and longitude of the point on the Earth where the Sun stands exactly overhead at the chosen epoch. Reference to “The Star Almanac for Land Surveyors”, NP321 prepared by HM Nautical Almanac Office, pages 74 and 75, which list annual polynomial coefficients for calculating solar declination and for conversion between sidereal and universal time.	$\Phi_{Sun}, \lambda_{Sun}$
$\Phi_{Sun}, \lambda_{Sun}$	2. By adding 180° to longitude and reversing the sign of latitude, find the position of the centre of the Earth’s night side shadow. $\Phi_{Shadow} = -\Phi_{Sun}$ $\lambda_{Shadow} = \lambda_{Sun} + 180^\circ$	$\Phi_{Shadow}, \lambda_{Shadow}$
Satellite x, y, z	3. Using the satellite’s 3-dimensional Earth centred coordinates, calculate the radius of the satellite’s orbit at that epoch. $h_s = \sqrt{x_s^2 + y_s^2 + z_s^2}$	h_s
$\Phi_{Shadow}, \lambda_{Shadow}, h_s$	4. Convert the shadow centre coordinates to Earth-centred 3-dimensional coordinates at the radius of the satellite orbit at epoch – assuming spherical Earth. $x_{ecl} = h_s \cdot \cos \varphi \cdot \cos \lambda$ $y_{ecl} = h_s \cdot \cos \varphi \cdot \sin \lambda$ $z_{ecl} = h_s \cdot \sin \varphi$	$x_{ecl}, y_{ecl}, z_{ecl}$
R_S, R_E, D_E	5. Using the radii of the Sun and the Earth, and the average distance from Sun to Earth, calculate the convergence of the shadow zones (umbra and penumbra) in the direction away from the Sun. This gives the radii of the eclipse zones at satellite instantaneous altitude.	R_{Umbra} $R_{Penumbra}$

End of table 2.3

	Sun radius is 1392000 km Earth radius is 6378 km Mean distance Sun to Earth is 149597890 km $\tan u = \left(\frac{1392000 - 6378}{149597890} \right)$ $\tan p = \left(\frac{1392000 + 6378}{149597890} \right)$ $R_{Umbra} = a - h_s \cdot \tan u$ $R_{Penumbra} = a + h_s \cdot \tan p$	
R_{Umbra} $R_{Penumbra}$ Satellite x_s, y_s, z_s	6. Now calculate the distance (D) from the shadow centre to the satellite and compare with the eclipse zone radii to determine whether or not the satellite is in half shadow (penumbra) or in full shadow (umbra) $D = \sqrt{(x_s - e_{ecl})^2 + (y_s - y_{ecl})^2 + (z_s - z_{ecl})^2}$ If D is less than R_{Umbra} then the satellite is in eclipse If D is greater than R_{Umbra} and less than $R_{Penumbra}$ then the satellite is in semi-eclipse	Eclipse yes/no

Application of this process takes place in the program after the visibility is determined. In other words, once the program has decided that a satellite is visible above the mask angle, the program then tests whether that satellite is at the same time in Earth's shadow (Annex D).

2.7. Conclusions of Chapter 2

1. Broadcast and precise ephemeris computation algorithms are developed and programmed in order to develop satellite and receiver positions, and to find out when satellites enter eclipse.
2. Meanwhile, published software systems were not found completely suitable, although some published routines were used for comparison purposes to check the correctness of own programs.
3. There were a number of advantages to preparing programs rather than trying to adapt third party software. Notable was that a detailed understanding of the computations involved for this specific purpose

was absolutely necessary. Additionally, difficulties encountered pointed at a number of less well-understood pitfalls that hopefully are dealt with in proprietary software, while here, having prepared own software, there were clear guarantee that these pitfalls had been overcome.

Analysis of the Earth's Shadowing Effects

Precise positioning by GNSS might incur some error when one or more of the satellites that are being observed happen to be in Earth shadow – in eclipse. This effect might be worsened if the Earth is passing through a period of stormy solar weather. It is therefore of considerable interest to be able to examine satellite orbit changes when a satellite passes Earth's shadow.

This chapter develops the connection between the methods of describing the motion of the Sun and GNSS satellites in, respectively, the astronomical and the Earth centred systems.

Published one topic of this chapter by author (Zubinaite, Preiss 2010, 2011).

3.1. Determining the Earth's Shadow Zone

Determining whether or not orbiting satellites are in eclipse clearly requires a definition of an area in space, which is eclipsed. In its very simplest form, this area can be thought of as a circular surface produced by the intersection of the umbral cone with the geopotential surface on which a given satellite is riding. If then the boundaries of this surface can be defined in the form of conventional 3D Earth-centred coordinates, the simple comparison with satellite coordinates

at epoch will immediately show whether the satellite is eclipsed. It is thus not necessary to be concerned with the shape of the actual surface – it is the surface's boundary, which is of interest.

The strategy selected requires the following input information at epoch:

- The distance from the centre of the Sun to the centre of the Earth – average 149 597 890 km;
- The radius of the Sun, assuming a spherical Sun, in distance – 1 392 000 km;
- The radius of the Earth, assuming a spherical Earth – 6378 km;
- The radius of the satellite orbit, assuming a circular path – 26578 km.

The computing process is as follows:

1. Establish the Earth-centred coordinates of the centre of the Earth's shadow at satellite orbit altitude:
 - a) Using solar ephemerides, extract the latitude and longitude of the point on the Earth's surface where the Sun is at the zenith at epoch.
 - b) Change the sign of latitude, and add 180° to the longitude to obtain the latitude and longitude of the point on the Earth's surface opposite the previous point.
 - c) Add the altitude of the satellite orbit to the Earth's radius to obtain the latitude, longitude and height of the satellite.
 - d) Convert to Earth centred three dimensional coordinates
2. Establish the radius of the shadow plane at satellite altitude:
 - a) Compute the convergence of the shadow cone due to the difference in radius between the Sun and the Earth.
 - b) The compute the radius of the shadow plane – 6132 km.
3. Extract the satellite ephemeris parameters at epoch:
 - a) Compute the satellite's Earth centred coordinates at epoch.
 - b) Subtract the coordinates of the shadow plane centre.
 - c) Compute the distance by three-dimensional Pythagoras.
4. Determine whether the satellite is in eclipse:
 - a) If the distance from step 3.c is smaller than the distance from step 2.b, then the satellite is in eclipse.
 - b) If the distance from step 3.c is greater than the distance from step 2.b. then the satellite is not in eclipse.

3.2. Influence of Earth Shadow on Satellite Orbit

The aim of this investigation is to find significant differences in satellite orbits, in other words, to look at the satellite position variations during Earth shadow. In particular, it might be logically assumed that orbit disturbances due to solar pressure would not take place when the satellite is in Earth's shadow - eclipse.

Determining whether or not orbiting satellites are in Earth's shadow clearly requires a definition of the area in space, which is eclipsed. In its simplest form, this area can be thought of as a circular surface produced by the intersection of the umbral cone with the geopotential surface on which a given satellite is riding. If then the boundaries of this surface can be defined in the form of conventional 3D Earth-centred coordinates, then simple comparison with satellite coordinates at epoch will immediately show whether the satellite is in Earth's shadow.

The algorithms for computing Earth's shadow periods were tested by means of hand computations in order to provide validation results. Thereafter, appropriate program routines were drafted. The routines were finally connected together in a full program that was thoroughly tested and then compiled into an executable form. All programming work was done using the FBIDE program editor into the Quick Basic programming system.

Records of solar activity were systematically examined for the January 2012. Solar polynomials for this period were collected and individual satellite eclipse periods were computed and recorded. Polynomials describing the Sun's motion were sourced from the Star Almanac for Land Surveyors published by Her Majesty's Nautical Almanac Office in the United Kingdom. These polynomials provide for the computation of the Sun's declination and the difference between the Greenwich hour angle of the Sun and Universal Time at any epoch throughout the calendar year.

The first task was to determine the visibility of satellites over a 15° elevation cut-off during the selected period— and then to find which of the visible satellites at any time in the period were actually going through Earth's shadow.

Figure 3.1 is an example of the report of the written program (Annex D), which determines which satellites are in Earth's shadow. The program produces reports for each day separately, showing all GPS satellites when they appear in Earth's shadow. In this report, the horizontal axis represents 24 hours, and the vertical axis is the list of satellites. The meanings of the symbols used describing the conditions of the satellite are shown below in each report.

SATELLITE AVAILABILITY AND ECLIPSE REPORT

For Latitude: 60 39 4.8 Longitude: 10 55 42.4
 For Mask Angle: 15 degrees
 On date: 10282003 (mm dd yyyy)

Sat#	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	2	2	2	2		
	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3
PG01	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG02	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG03	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG04	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG05	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG06	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG07	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG08	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG09	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG10	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG11	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG12	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG13	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG14	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG15	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG16	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG17	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG18	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG19	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG20	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG21	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG22	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG23	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG24	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG25	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG26	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG27	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG28	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG29	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG30	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG31	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
PG32	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:

^ = visible; @ = in eclipse; □ = in penumbra

Fig. 3.1. Report of GPS satellites in Earth's shadow at 23 January 2012

A summary of all performed daily reports is given in table 3.1 showing which satellites are in an eclipse season during January in 2012. In total, there are nine GPS satellites in eclipse during this period.

Table 3.1. Satellites in Earth's shadow zone in January 2012

January, 2012																															
PRN	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31

During each year there are one – two periods when a given GPS satellite enters the Earth's shadow on every revolution. The eclipse season lasts four to eight weeks every six months. The Earth's shadow lasts up to one hour (GPS ≤ 54 min, GLONASS ≤ 53 min) (Dilssner, Springer, Gienger, Zandbergen 2011). During these eclipse seasons larger thermal variations occur within the spacecraft than the rest of the year and accordingly may cause larger clock frequency variations. These variations are removed during the production of precise ephemerides, but they are not removed during the generation of broadcast ephemerides and may have a direct impact on their quality.

As a sample of the GPS satellite tracking in their orbit and demonstrating the period of PRN14 satellite tracking across the Earth's shadow zone is illustrated in figures 3.2–3.13. The results are described in the form of differences between broadcast and precise ephemerides in meters with 15 minute intervals.

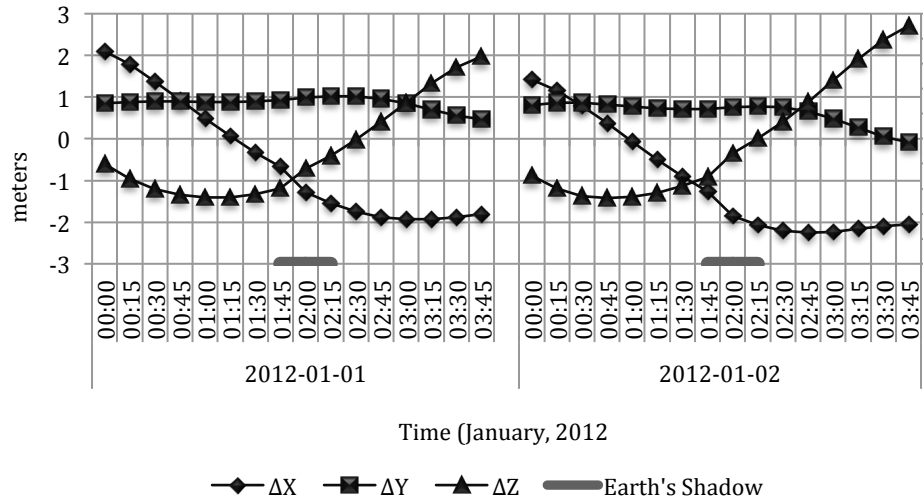


Fig. 3.2. PRN14 Broadcast orbit error with respect to IGS final orbit, and showing the satellite tracking in Earth's shadow at 01–02.01.2012

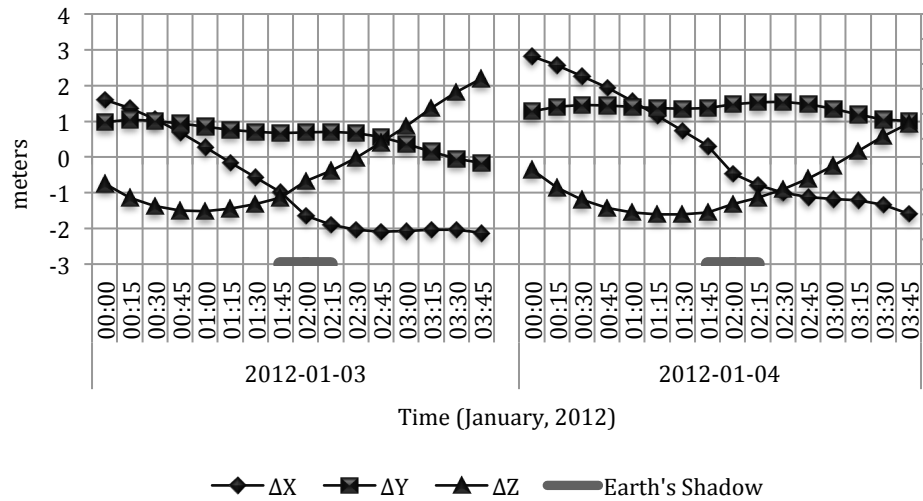


Fig. 3.3. PRN14 Broadcast orbit error with respect to IGS final orbit, and showing the satellite tracking in Earth's shadow at 03–04.01.2012

Figure 3.2 and 3.3 plots the differences between broadcast orbit errors with respect to IGS final orbit in three –dimensions (3D), and illustrating the GPS satellite tracking in Earth's shadow at 03–04.01.2012. As the results show, the range of the differences is about 0.09–2.83 meters in no Earth's shadow, and

differences reaches between 0.00–2.07 meters in Earth's shadow. The broadcast and precise ephemerides differences of the selected satellite show that the differences from case when GPS satellites pass the Earth's shadow and the case when satellites are not in Earth's shadow results does not make any significant signs.

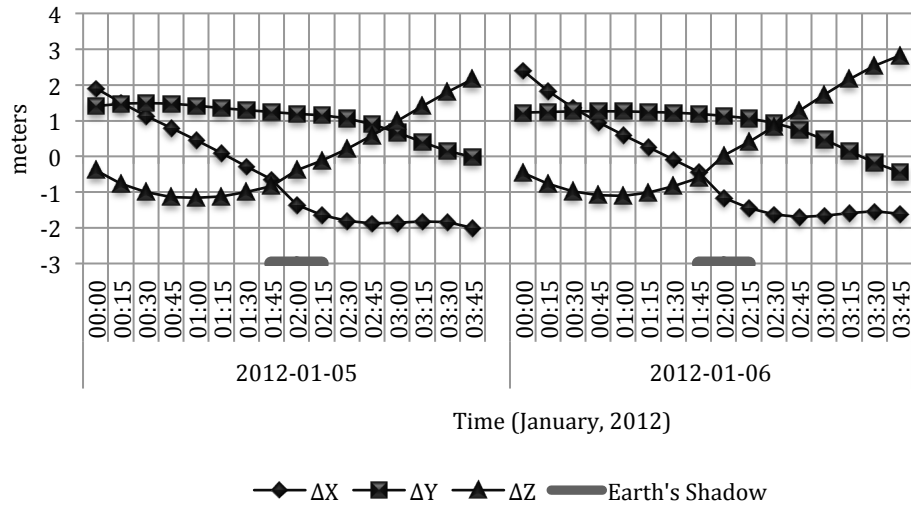


Fig. 3.4. PRN14 Broadcast orbit error with respect to IGS final orbit, and showing the satellite tracking in Earth's shadow at 05–06.01.2012

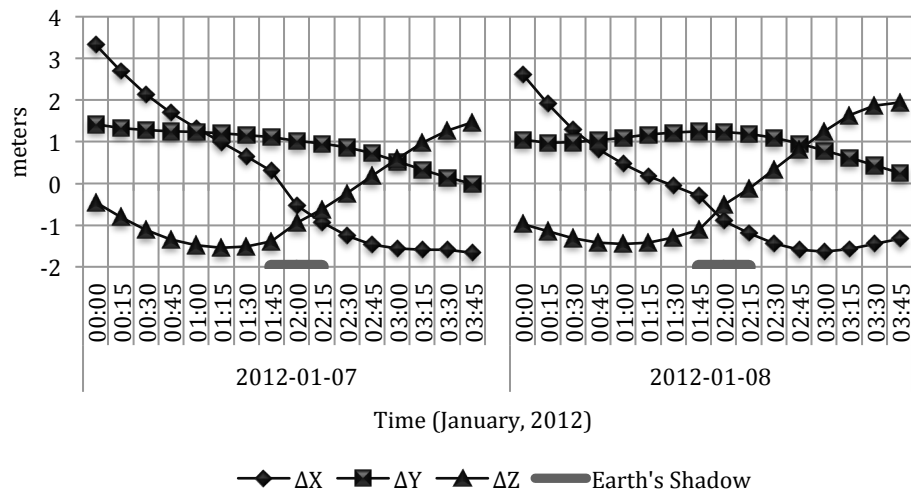


Fig. 3.5. PRN14 Broadcast orbit error with respect to IGS final orbit, and showing the satellite tracking in Earth's shadow at 07–08.01.2012

Figure 3.4 and 3.5 plots the differences between broadcast orbit errors with respect to IGS final orbit in three –dimensions, and illustrating the GPS satellite tracking in Earth's shadow at 05–08.01.2012. As the results show, the range of the differences is about 0.01–3.34 meters in no Earth's shadow, and differences reaches between 0.29–1.64 meters in Earth's shadow.

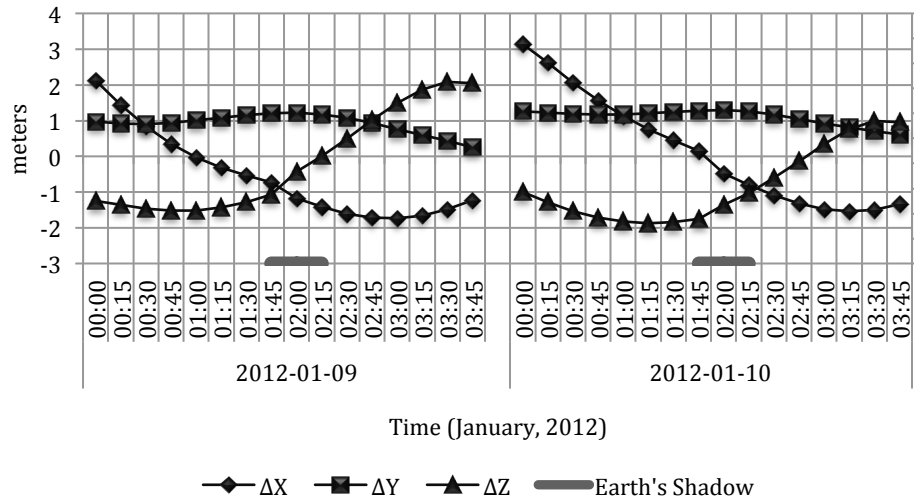


Fig. 3.6. PRN14 Broadcast orbit error with respect to IGS final orbit, and showing the satellite tracking in Earth's shadow at 09–10.01.2012

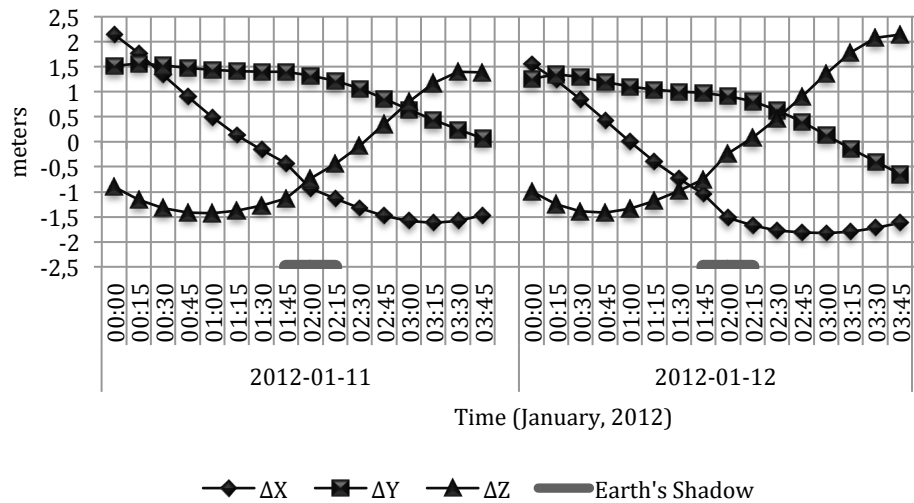


Fig. 3.7. PRN14 Broadcast orbit error with respect to IGS final orbit, and showing the satellite tracking in Earth's shadow at 11–12.01.2012

Figure 3.6 and 3.7 plots the differences between broadcast orbit errors with respect to IGS final orbit in three –dimensions, and illustrating the GPS satellite tracking in Earth's shadow at 09–12.01.2012. As the results show, the range of the differences is about 0.25–3.14 meters in no Earth's shadow, and differences reaches between 0.002–1.76 meters in Earth's shadow.

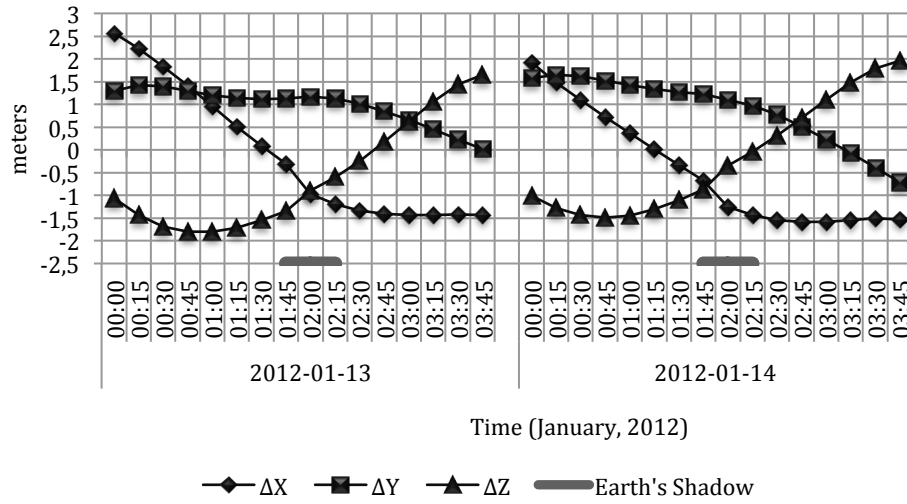


Fig. 3.8. PRN14 Broadcast orbit error with respect to IGS final orbit, and showing the satellite tracking in Earth's shadow at 13–14.01.2012

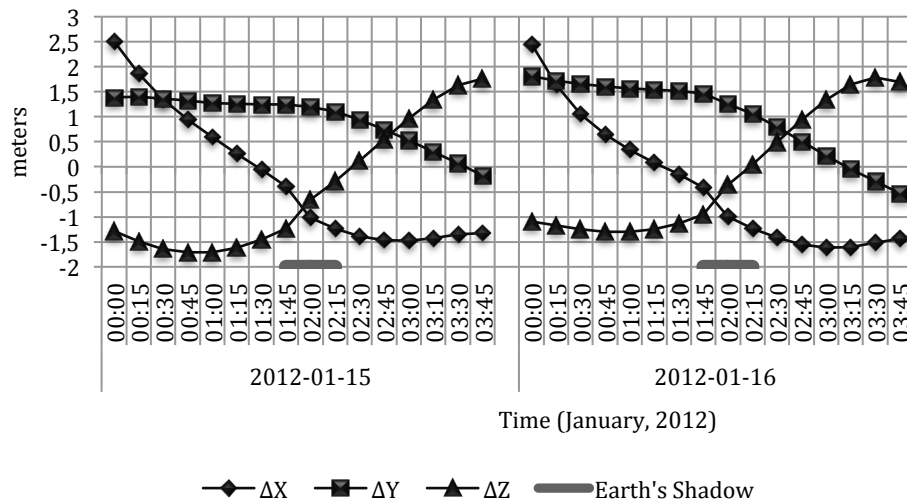


Fig. 3.9. PRN14 Broadcast orbit error with respect to IGS final orbit, and showing the satellite tracking in Earth's shadow at 15–16.01.2012

Figure 3.8 and 3.9 plots the differences between broadcast orbit errors with respect to IGS final orbit in three –dimensions, and illustrating the GPS satellite tracking in Earth's shadow at 13–16.01.2012. As the results show, the range of the differences is about 0.54–2.57 meters in no Earth's shadow, and differences reaches between 0.04–1.43 meters in Earth's shadow.

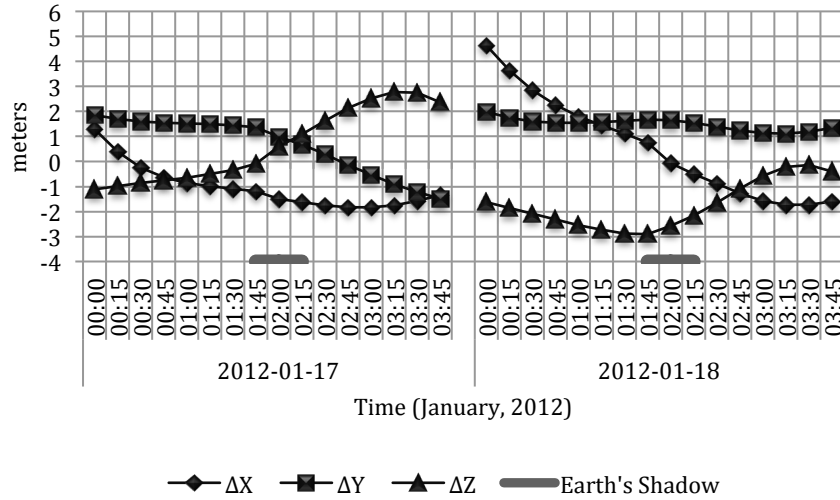


Fig. 3.10. PRN14 Broadcast orbit error with respect to IGS final orbit, and showing the satellite tracking in Earth's shadow at 17–18.01.2012

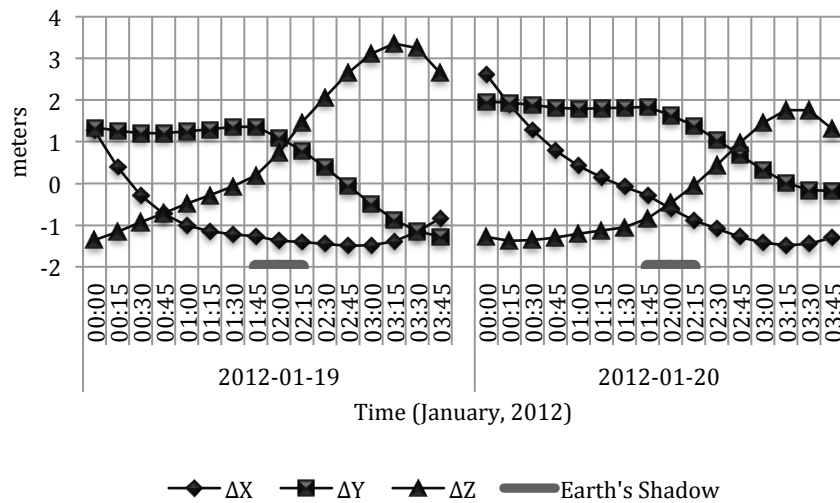


Fig. 3.11. PRN14 Broadcast orbit error with respect to IGS final orbit, and showing the satellite tracking in Earth's shadow at 19–20.01.2012

Figure 3.10 and 3.11 plots the differences between broadcast orbit errors with respect to IGS final orbit in three –dimensions, and illustrating the GPS satellite tracking in Earth's shadow at 17–20.01.2012. As the results show, the range of the differences is about 0.13–4.65 meters in no Earth's shadow, and differences reaches between 0.29–2.92 meters in Earth's shadow.

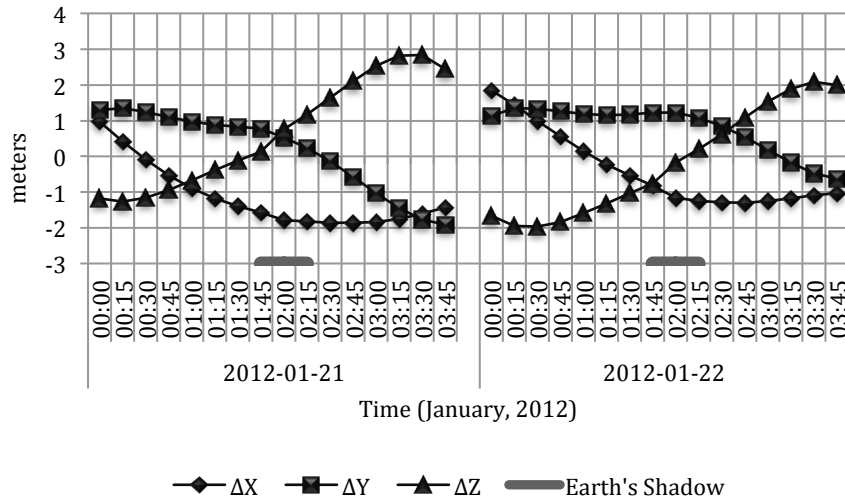


Fig. 3.12. PRN14 Broadcast orbit error with respect to IGS final orbit, and showing the satellite tracking in Earth's shadow at 21–22.01.2012

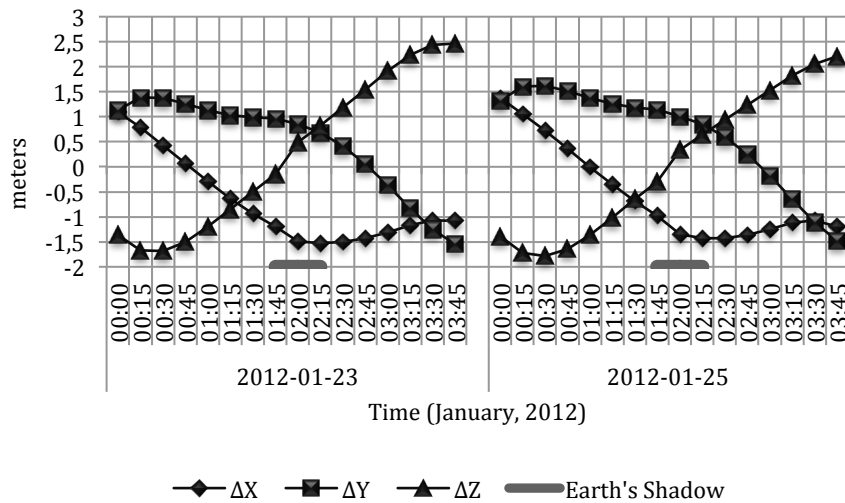


Fig. 3.13. PRN14 Broadcast orbit error with respect to IGS final orbit, and showing the satellite tracking in Earth's shadow at 23–24.01.2012

Figure 3.12 and 3.13 plots the differences between broadcast orbit errors with respect to IGS final orbit in three –dimensions, and illustrating the GPS satellite tracking in Earth's shadow at 21–25.01.2012. As the results show, the range of the differences is about 0.13–2.84 meters in no Earth's shadow, and differences reaches between 0.24–1.82 meters in Earth's shadow.

In summary, investigation shows that, in all cases the characteristics of satellite positions in the Earth's shadow and not in the Earth's shadow are very close. In other words, changes of satellite orbiting when it crosses the Earth's shadow are not seen, when comparing with the rest of the investigated period.

3.3. Conclusions of Chapter 3

1. The theory and methods for the investigation of the effects of Earth's shadowing on a satellite positioning in orbit are presented. The written program calculates which satellites are eclipsed and when.
2. The investigation shows that one or more of the satellites that were observed were around one hour in Earth's shadow. The broadcast orbit error with respect to IGS final orbit reaches up to 4 meters. The differences of ephemerides passing the Earth's shadow do not show changes. As a result, the evidence suggests that observations to satellites that are in Earth's shadow make no significant differences.
3. The reason why results do not make any remarkable changes, could be because satellite positions are not so much diverted in their orbital path in Earth's shadow as the others, and are therefore introducing a less random element into what otherwise should be expected. Also, evaluations show that there are just one or two satellites in Earth's shadow at any time.

Analysis of the Solar Storming Effects on Global Navigation Satellite Systems Satellites Orbits and Ground Positioning Vectors

The purpose of this chapter is to investigate and determine the effects of specific solar storming events on GNSS navigation systems. This chapter discusses the possible effects of space weather activity and uses tracked observational data to investigate the effect of specific solar storms on vector positioning.

Published one topic of this chapter by author (Zubinaite, Preiss, 2010, Zubinaite, Preiss, 2011).

4.1. Tools and Techniques of the Analysis

The aim is to process data over longer periods of time (up to one month) with as short as possible interval between each observation epoch (1 second).

The experimental work is based on the theoretical method of satellite orbit and ground receiver position determination. The procedure used is made up of a sequence of several steps. The following is a summary of the necessary experimental steps:

1. Extract the solar storm events in January 2012.
2. Extract the broadcast ephemerides and precise IGS final orbits for the GPS satellites for January 2012.
3. Compute the satellite orbit positions for every 15 minutes using the broadcast ephemerides for each epoch for January 2012, including solar activity and no solar activity periods.
4. Compute the precise satellite orbit positions using final IGS orbits, including solar activity and no solar activity periods for the same epochs as above.
5. Compare the precise and broadcast orbital positions.
6. Compute positional vectors between selected pairs of CPOS stations.
7. Compare results of vectors solutions.

Available Data. Archived ephemeris and observation data is readily available from 2002, thus determining the start of the research period. Identification of reported days with high solar pressure was the starting point of the research.

Days when there were no reported solar flares were to be examined in order to give an idea of the extent of an orbit disturbance during a „clean“ day, as well as the extent of the differences in X, Y and Z coordinates between predicted and precise orbit computations. Then, these differences were to be used as a baseline for further data comparison and investigation. In the event, it was decided to concentrate on data for the whole month of January 2012 because there occurred during that month a number of discrete solar events as well as „clean“ periods for which the latest and highest quality tracking data were available.

NOAA Space Weather Scales. The Space Weather Prediction Center (SWPC) has developed and introduced so-called „NOAA Space Weather Scales“ as a way to communicate to the general public the current and forecast space weather conditions and their possible effects on people and systems. Many of the SWPC products describe the space environment, but few have described the effects that can be experienced as the result of environmental disturbances. Three categories are used by the SWPC to describe different types of space weather that are most relevant for possible effects on satellite-based and other systems. These are:

1. Geomagnetic storms – disturbances in the geomagnetic field caused by gusts in the solar wind that blows towards the Earth;

2. Solar radiation storms – elevated levels of radiation that occur when the numbers of energetic particles increase;
3. Radio blackouts – disturbances of the ionosphere caused by X-ray emissions from the Sun, resulting in severe interference in radio traffic.

Within each of these three categories, the SWPC has defined five levels (or “scales”) of severity, numbered from 1 to 5 (from minor to extreme). These are the definitions used for reporting activity in regularly published weekly summaries. Essentially, geomagnetic storm categories G2 to G5 and solar radiation storm categories S2 to S5 can affect satellite navigation and, specifically, can have the effect of altering satellite orbits.

Storms Selected for study. The SWPC web site indicates that solar storms were recorded during the 2002-2012–time period.

According to SWPC messages, detailed reports of solar events during 01-31, January 2012 were as described below:

Active sunspot number 1401 erupted on January 19, 2012, producing an M3-class solar flare and a coronal mass ejection (CME). The CME’s expanding cloud is heading almost directly toward Earth and is due to strike 22:30 UTC +/- 7hrs on 21 January 2012.

An active region on the Sun has spawned an M8.7 eruption – nearly an X-flare – that blasted a stream of charged particles toward Earth, due to arrive January 24, 2012. The eruption took place on January 23, 2012 UTC 03:59, and came from sunspot 1402, on a part of the Sun that recently turned into view and has been active for several days. The leading edge of the resulting stream of charged particles reached Earth on approximately January 24 14:00 UTC hrs. Experts at NOAA’s Space Weather Prediction Center are saying it is the strongest radiation storm since 2005.

Determination of the start for selected days (January, 2012) of solar activity was chosen all day of the day when the solar burst started. Intervals of one second were chosen. The idea is to do computations for intervals small enough to capture variations in the GPS orbits, because this would give a most realistic chance of finding out possible orbit disturbances during these days of high solar activity. The shortest interval, of course, would always provide most complete information

The end of the detailed examination period was decided to be 31 January 2012 in the expectation that by then conditions would have become storm-free again.

Tracking Data. Satellite-based navigation and positioning systems are widely used throughout the world. It is well known that these systems are vulnerable to space weather events, but current monitoring and prediction services do not provide information about exactly when and where these systems are or will be disturbed by such events or the magnitude of the disturbance that

will experienced by users. As part of an effort toward investigating this and establishing such services, the effects of space weather events on the CPOS national positioning service have been studied. CPOS is operated by the Norwegian Mapping Authority (NMA) (Figure 4.1).

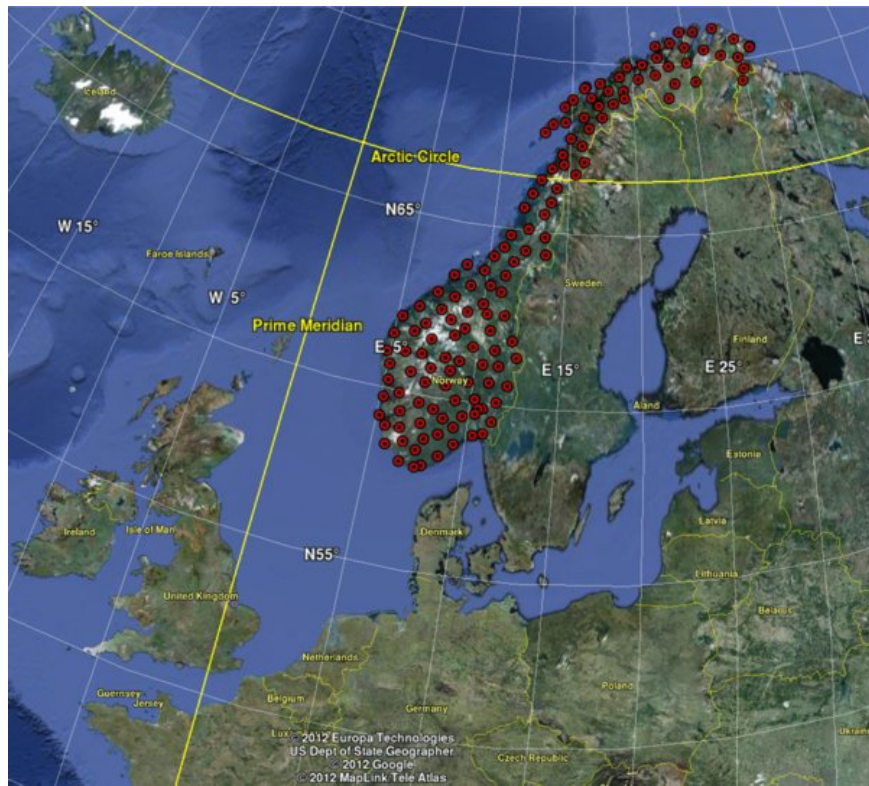


Fig. 4.1. Permanent Norwegian Mapping Authority (NMA) CPOS stations in Norway

The maximum separation between adjacent stations is 70 km, while a typical distance is around 50–60 km. CPOS is a Norwegian service for both GPS and GLONASS users, which is available with a precision of one centimetre, through an auxiliary system called Position Accuracy on the Centimetre level. Distributed via both GSM telephone and the Internet, the service covers large parts of Norway and is easy to use. CPOS is intended for professional users that require great precision. CPOS provides real-time corrections via GSM, which when used in connection with GPS receivers, permit calculation of position to one centimetre accuracy. In the CPOS system, a virtual reference station is calculated on the basis of the coverage cell in which the user is located. For the user, the system then functions as if the base station were close at hand.

Precise orbits, with 15 minutes sample interval, were obtained from the IGS website managed by Jet Propulsion Laboratory of the California Institute of Technology. This IGS website provides GNSS data and products to the scientific community. The IGS website maintains precise orbit records from 1992 which are stored in SP3 format. The accuracy of precise final orbit data is generally less than 0.05 meters (International GPS Service for Geodynamics (IGS) Website, 2002).

4.2. Comparison of Broadcast and Precise Ephemerides

The aim here is to compute GPS satellite coordinates using broadcast ephemeris data in order to compare them to precise post-mission data.

The Keplerian parameters generated from the broadcast satellite navigation messages were used to calculate satellite coordinates at 15 minutes intervals. These predictive coordinates were compared with the precise ephemeris coordinates read directly from the IGS files and plotted. The reason for choosing a 15 minute interval was to avoid interpolation errors, while providing sufficient data to analyse the position differences.

The methods and formulæ used are described in Chapter 2.

The differences between the broadcast and precise X, Y and Z coordinates are plotted for day 21 (Figure 4.2–4.4) with respect to time. The rest of the graphs, which represent results for day 20 and 22–25 are in appendix E.

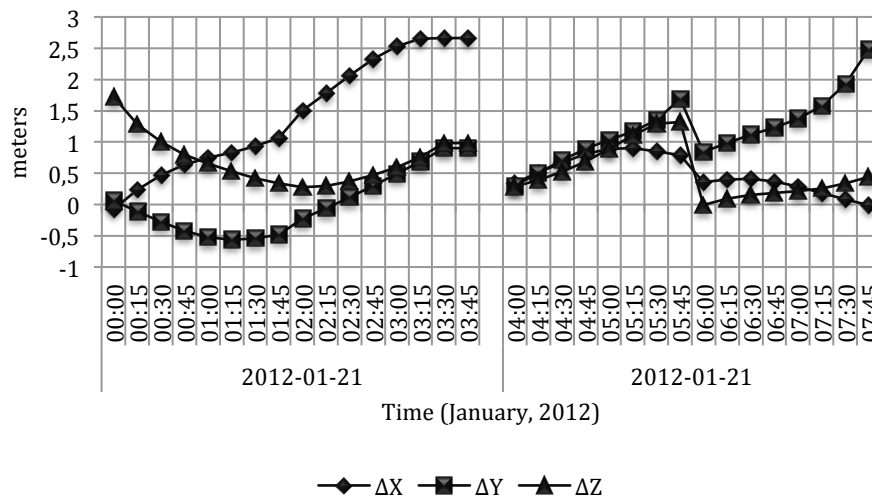


Fig. 4.2. PRN01 Broadcast orbit error with respect to IGS final orbit at 21.01.2012 between 00:00–08:00 time

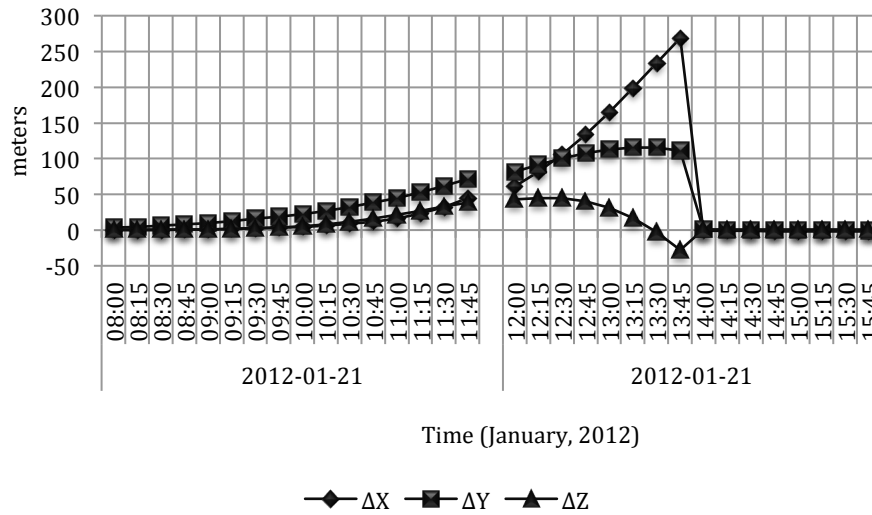


Fig. 4.3. PRN01 Broadcast orbit error with respect to IGS final orbit at 21.01.2012 between 08:00–16:00 time

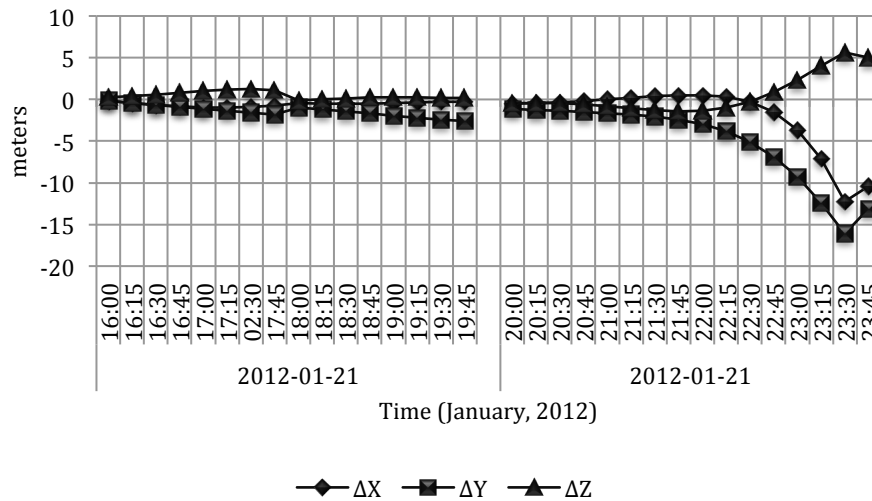


Fig. 4.4. PRN01 Broadcast orbit error with respect to IGS final orbit at 21.01.2012 between 16:00–24:00 time

Figure 4.2–4.4 plots the abscissa, which shows the differences between the coordinates in meters when comparing broadcast and precise ephemerides. Attention should be paid to the scale of the differences. The scale of the results shows disagreement of up to more than hundred meters between broadcast orbit

and precise final orbit. The differences range: 177.38 meters on day 20; 268.43 meters – day 21; 313.53 meters – day 22; 305.72 meters – day 23; 263.07 meters – day 24; 114.214 meters – day 25. This is larger than expected and it can be concluded that the ephemeris file had substantial errors. In other words, differences between the precise and the broadcast ephemeris may be the result of anomalies, or problems with the data. Data problems may be because of incorrect or misinterpreted precise ephemeris SP3 format files and/or observational RINEX files. The plots indicate that a large number of outliers repeat with a time period of approximately 12 hours.

Additionally, it is suggested that a cause of the differences is that the satellite orbit parameters of the broadcast orbit are approximations of the true orbit and maybe because of perturbation in the orbit, the coordinates are going to be less accurate than the precise orbit calculations. The discontinuities are likely caused by transition from using the one predictive ephemeris record to another. Making more frequent broadcast ephemeris updates so that errors are not propagated as much could reduce these discontinuities.

4.3. Influence of Global Navigation Satellite System Satellite Orbits Positions Definitions on Ground Positioning Vectors

The focus of this part of the study is the analysis of the effects of satellite orbit errors on the accuracy of ground positions determined by short, middle and long vectors. It was decided to compute vectors using day and night observations together, and then to compute the vectors for day and night separately. The reasoning was that ionospheric effects are logically expected to be greater during daytime.

The ionosphere, which reflects HF radio waves, is the upper part of the Earth's atmosphere and is considered to be a part of the space weather environment. The ionosphere extends from around 50 km to 500 km in altitude and is characterised by the presence of free electrons, which can reflect radio waves back to Earth. The greater the density of free electrons, the greater the frequency of radio waves that can be reflected. The free electrons in the ionosphere result from ionisation of atoms and molecules by solar radiation (Berkner, Wells, Seaton 1939).

Variations in chemical composition and atmospheric dynamics lead to the formation of a number of distinct bands or layers. These regions of particularly high electron density are labelled in order of increasing altitude as the D, E, F1 and F2 regions. With the coming of night and the absence of solar ionising

radiation, the electron density in the D, E and F1 regions becomes very low. The electron density of the F2 region is also reduced at night but persists in a weakened state due to winds in the upper atmosphere, which carry electrons from the dayside to the night-side. Reflections from the night-side ionosphere thus occur only from the F2 region (called the F region at night). Both the D and F regions of the ionosphere are highly sensitive to variations in space weather and solar activity. The interaction of HF radio waves with the D and F regions varies greatly with the seasons, throughout the day and night and throughout the solar cycle (Berkner, Wells, Seaton 1939).

Index 95 (“I95”) values reflect the intensity of ionospheric activity, i.e., the expected influence on the relative GPS positions. I95 values are computed from the ionospheric corrections for all satellites at all network stations for the respective hour. The worst 5% of data are rejected.

Large values of the ionospheric I95 index indicate that difficulties may be encountered in GPS baseline processing (delayed ambiguity resolution, reduced positioning accuracy). Often these difficulties can be mitigated by longer observation periods. Experience from the last solar maximum showed that even the technique of virtual reference stations might be subject to complications if large I95 values are observed.

Evaluation of short, middle and long baseline vectors has been done to estimate accuracy in three dimensions. Observational data processing has been performed using the Trimble Total Control software, and the results are presented in the following sections 4.3.1–4.3.3.

Short vectors were tested because such vectors are of most interest to the land surveying profession, where repeatabilities at well below 1 ppm (1 mm per km) can be required. Short baseline length is in the range from 1 km to several km.

Middle length vectors, while clearly being required where short vectors are not possible, are of more interest in the creation and maintenance of national networks. With an eye to the future, such networks need to have internal consistency at precisions approaching 0.1 ppm. Baseline length is from 30 km to about 100 km.

Longer length vectors are mostly of advanced geodetic interest. However, the longer the vector, the greater the difficulty of having both terminals observing the same satellites at the same time, due to Earth curvature. As far as accuracy requirements at this level might be concerned, desired precision could be limited only by the imagination. (In other words – best possible or better). The length is in the interval from hundred km to thousands km.

4.3.1. Impact on Short Vectors

Data was processed for the short distance from CPOS station *Vardo* to *Vardo Havn*, a distance of 5.107 km. The results consisted of time series of values for the differences in X, Y and Z coordinates, and slant distances. Results were computed as single day results for each day throughout January 2012.

Changes in the positions are also compared with the previously mentioned solar storm events that coincide with the investigated time period. In other words, the aim is to discover the significant changes in the positions, as might be correlated with solar flares activity. Repeating that is expected in day 21, than there was produced M3-class solar flare and day 23 – M8.7-class solar flare, the result is geomagnetic storm being G1 (minor), day 27 – X1.7 class.

Comparison of graphs, which show solar activity peaks, seems to suggest that a lower M-class storm actually has a greater effect than a heavier M-class storm. Meanwhile, no clear correlation seems to be visible with X-class storming. The errors range approximately from 0.016-0.046 meters.

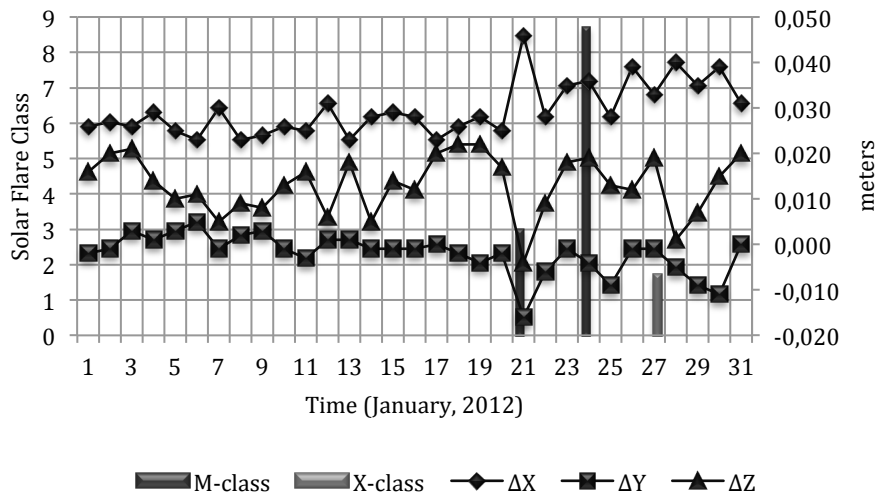


Fig. 4.20. ΔX , ΔY , ΔZ coordinates differences between Vardo and Vardo Havn with respect to time. Compared with solar flare classification rating

Figure 4.20 shows changes in differences of coordinates with respect to time. Also, compared with solar flare classification rating. The errors range: ΔX – 0.040 meters; ΔY – 0.005 meters; ΔZ – 0.022 meters. The errors range when it is solar activity: day 21 - ΔX – 0.046 meters; ΔY – 0.016 meters and ΔZ – 0.004 meters; day 24 – ΔX - 0.036 meters; ΔY – 0.004 meters; ΔZ – 0.019 meters.

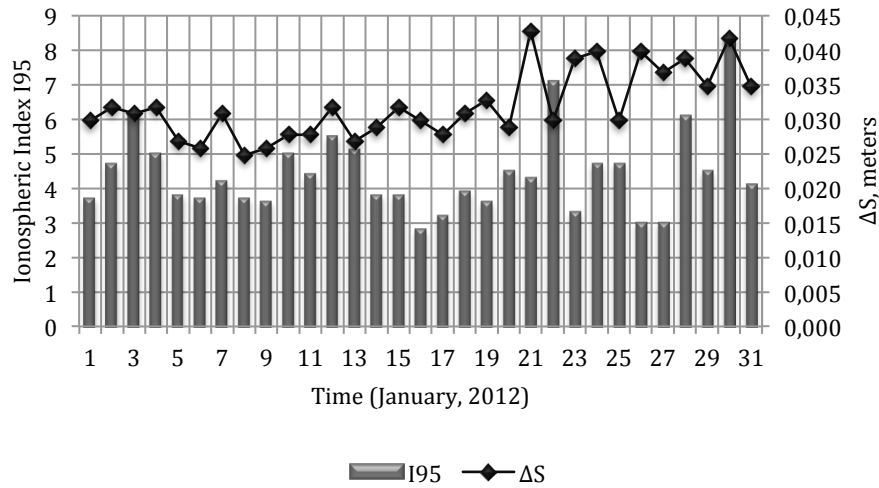


Fig. 4.21. Slope distance between Vardo and Vardo Havn. Comparison with ionospheric activity index I95 for all investigated time period

Figure 4.21 plots results of the slope distance between Vardo and Vardo Havn and comparing that with ionospheric index I95 results indicate the baseline of the positions does not smooth down with the values of effects of ionosphere.

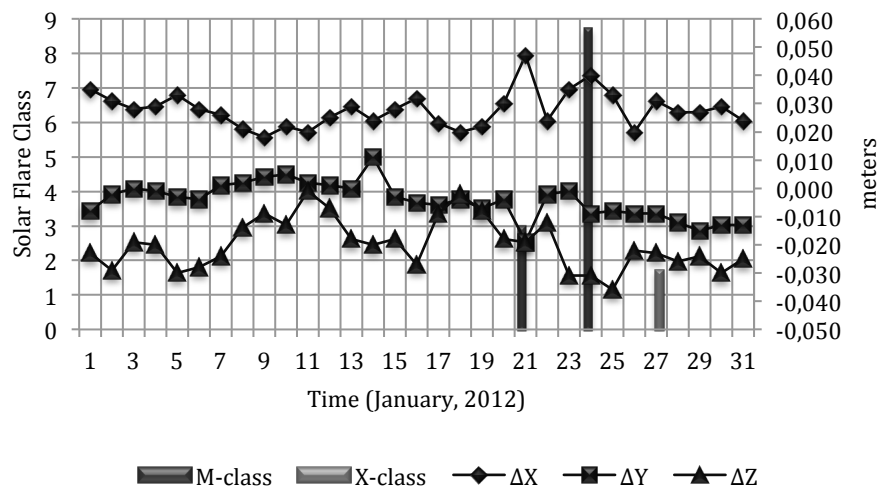


Fig. 4.22. dX, dY, dZ coordinates differences between Kristiansand and Tregde with respect to time. Compared with solar flare classification rating

The baseline Kristiansand – Tregde (figure 4.22) was selected in order to make more accurate determinations and to draw further conclusions. These stations are located in South of Norway and the distance between them is 22.496 km.

Figure 4.22 shows changes in differences of coordinates with respect to time. Also, compared with solar flare classification rating. The errors range: $\Delta X - 0.035$ meters; $\Delta Y - 0.011$ meters; $\Delta Z - 0.001$ meters. The errors range when it is solar activity: day 21 - $\Delta X - 0.047$ meters; $\Delta Y - 0.019$ meters and $\Delta Z - 0.019$ meters; day 24 - $\Delta X - 0.040$ meters; $\Delta Y - 0.009$ meters; $\Delta Z - 0.031$ meters.

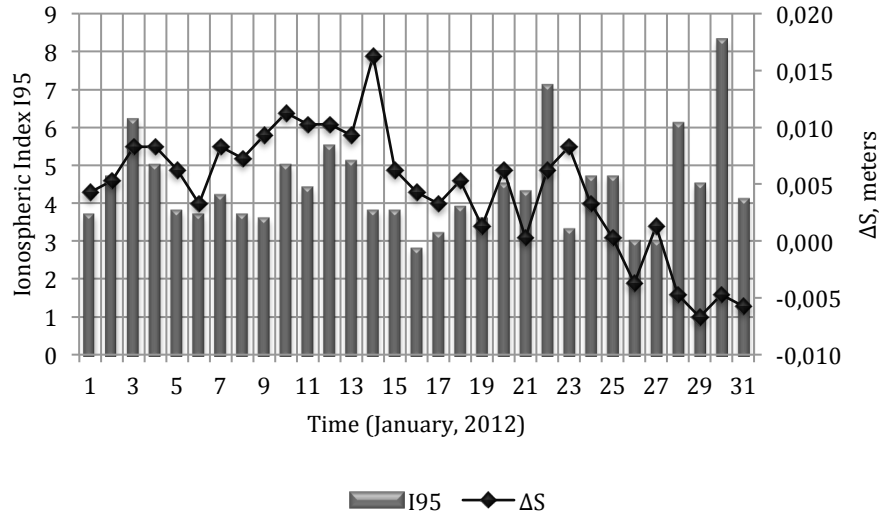


Fig. 4.23. Slope distance between Kristiansand and Tregde. Comparison with ionospheric activity index I95 for all investigated time period

Figure 4.23 plots the represent the slope distance between Kristiansand and Tregde, comparing with ionospheric index I95. Results indicate the baseline does not smooth with the values of the effect of ionosphere, as it is comparing baseline Vardo and Vardo Havn. Computed slope distance varies in -0.001–0.001 meters interval.

Comparison of graphs, which show solar activity peaks on short-range vectors, seems to suggest that a lower M-class storm actually has a greater effect than a heavier M-class storm. The following mean repeatabilities were obtained: day 21 - $\Delta X - 0.046-0.047$ meters; $\Delta Y - 0.016- 0.019$ meters; $\Delta Z - 0.004-0.019$ meters; day 24 - $\Delta X - 0.036-0.040$ meters; $\Delta Y - 0.004- 0.009$ meters; $\Delta Z - 0.019-0.031$ meters. When errors range in “clean” days: $\Delta X - 0.035-0.040$ meters; $\Delta Y - 0.005- 0.011$ meters; $\Delta Z - 0.001-0.022$ meters.

4.3.2. Impact on Middle Range Vectors

Data was processed for the middle distance from CPOS station the distance from *Longyearbyen* to *Svea* is 47.903 km. The results consisted of time series of values for the differences in X, Y and Z coordinates, and slope distances. Results were computed as single day results for each day throughout January 2012. These results are plotted in figures 4.24 with the incidence of M, X, and C-class events.

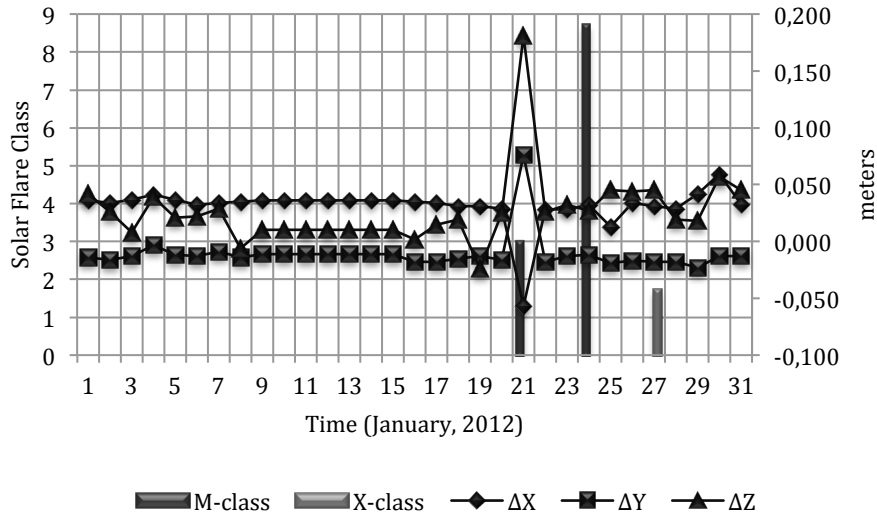


Fig. 4.24. ΔX , ΔY , ΔZ coordinates differences between Longyearbyen and Svea with respect to time

Figure 4.24 shows changes in differences of coordinates with respect to time. Also, compared with solar flare classification rating. The errors range: day 21 – ΔX – 0.057 meters; ΔY – 0.076 meters and ΔZ – 0.181 meters; day 24 – ΔX – 0.032 meters; ΔY – 0.012 meters; ΔZ – 0.027 meters. The errors range when no solar activity: ΔX – 0.059 meters; ΔY – 0.003 meters and ΔZ – 0.057 meters. Again, a lower M-class storm actually has a greater effect than a heavier M-class storm.

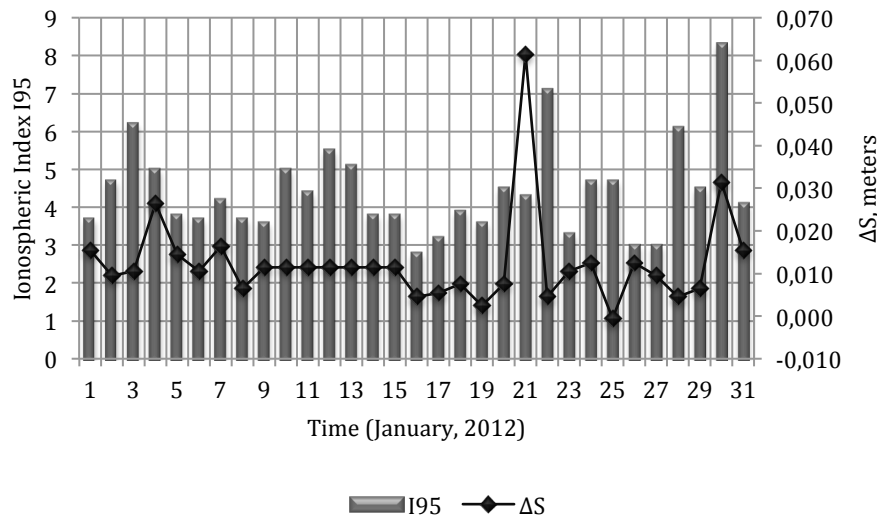


Fig. 4.25. Slope distance between Longyearbyen and Svea. Comparison with ionospheric activity index I95 for all investigated time period

Figure 4.25 plots the represent the slope distance between Kristiansand and Tregde, comparing with ionospheric index I95. Results indicate the baseline does not smooth with the values of the effect of ionosphere, as it is comparing baseline Vardo and Vardo Havn. Computed slope distance varies in -0.001–0.001 meters interval.

Data was processed for the middle distance from CPOS station. The distance from *Bergen* to *Stavanger* is 142.832 km. The results consisted of time series of values for the differences in X, Y and Z coordinates, and slant distances. Results were computed as single day results for each day throughout January 2012. These results are plotted in figures 4.26 with the incidence of M, X, and C-class events.

Figure 4.26 plots changes in differences of coordinates with respect to time. Also, compared with solar flare classification rating. The errors range: day 21 – ΔX – 0.048 meters; ΔY – 0.026 meters and ΔZ – 0.061 meters; day 24 – ΔX – 0.533 meters; ΔY – 0.556 meters; ΔZ – 0.465 meters. The errors range when no solar activity: ΔX – 0.046 meters; ΔY – 0.031 meters and ΔZ – 0.111 meters.

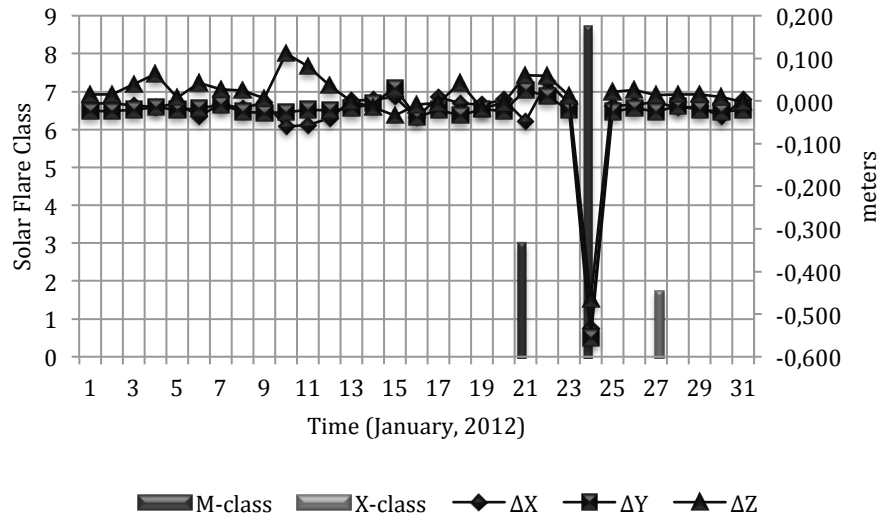


Fig. 4.26. dX, dY, dZ coordinates differences between Bergen and Stavanger with respect to time

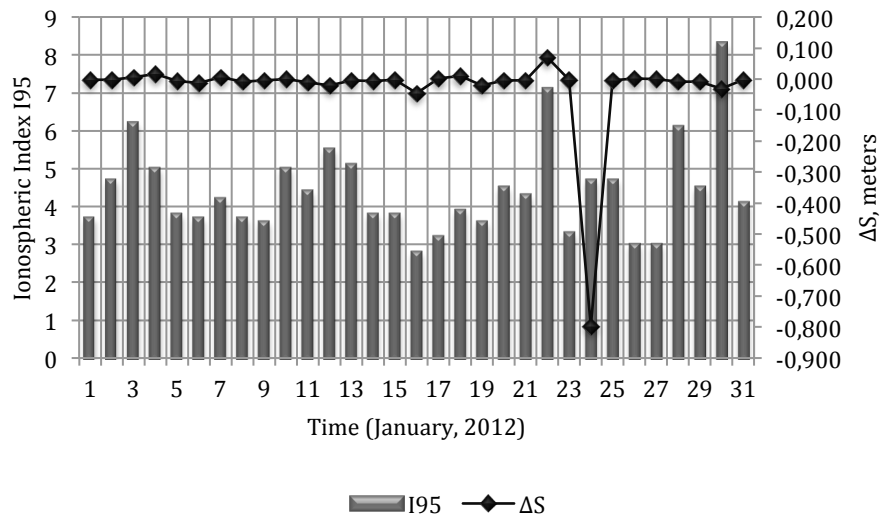


Fig. 4.27. Slope distance between Bergen and Stavanger. Comparison with ionospheric activity index I95 for all investigated time period

Figure 4.27 plots the represent the slope distance between Bergen and Stavanger, comparing with ionospheric index I95. Results indicate the baseline does not smooth with the values of the effect of ionosphere, as it is comparing baseline

Vardo and Vardo Havn. Computed slope distance varies in -0.001–0.001 meters interval.

4.3.3. Impact on Long Range Vectors

Data was processed for the long-range distance from CPOS station. The distance from Kristiansand to Stavanger is 170.033 km. The results consisted of time series of values for the differences in X, Y and Z coordinates, and slant distances. Results were computed as single day results for each day throughout January 2012. These results are plotted in figures 4.28 with the incidence of M, X, and C-class events.

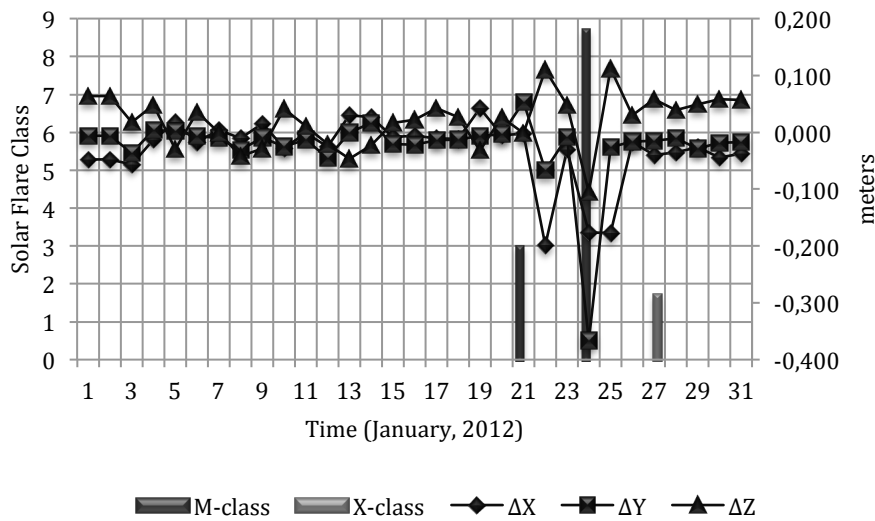


Fig. 4.28. ΔX , ΔY , ΔZ coordinates differences between Kristiansand and Stavanger with respect to time

Figure 4.28 plots changes in differences of coordinates with respect to time. Also, compared with solar flare classification rating. The errors range: day 21 – ΔX – 0.005 meters; ΔY – 0.004 meters and ΔZ – 0.027 meters; day 24 – ΔX – 0.176 meters; ΔY – 0.367 meters; ΔZ – 0.105 meters. The errors range when no solar activity: ΔX – 0.042 meters; ΔY – 0.054 meters and ΔZ – 0.112 meters.

Figure 4.29 plots the represent the slope distance between Bergen and Stavanger, comparing with ionospheric index I95. Results indicate the baseline does not smooth with the values of the effect of ionosphere, as it is comparing baseline Vardo and Vardo Havn. Computed slope distance varies in -0.001–0.001 meters interval.

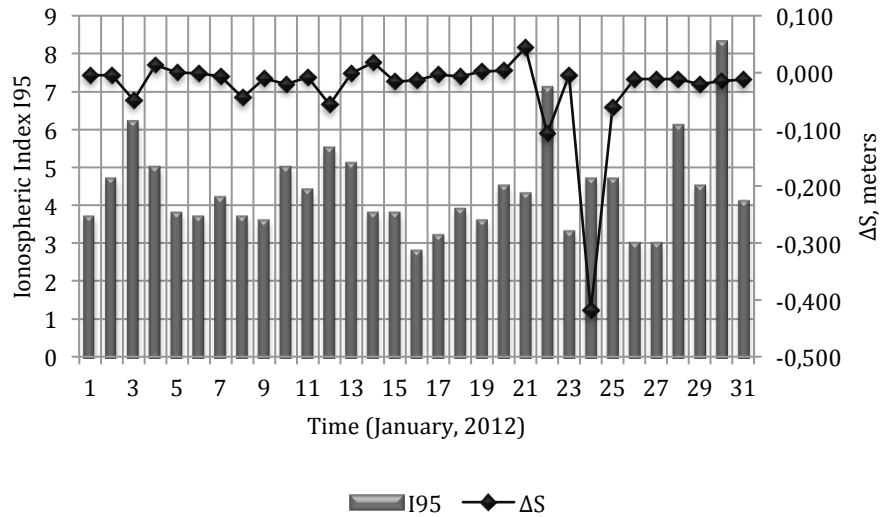


Fig. 4.29. Slope distance between Kristiansand and Stavanger. Comparison with ionospheric activity index I95 for all investigated time period

Another vector, Bodo – Andoya, was selected in order to make more accurate determinations and to draw further conclusions. The location of these stations is South of Norway and the distance between them is 231.371 km (Figure 4.30).

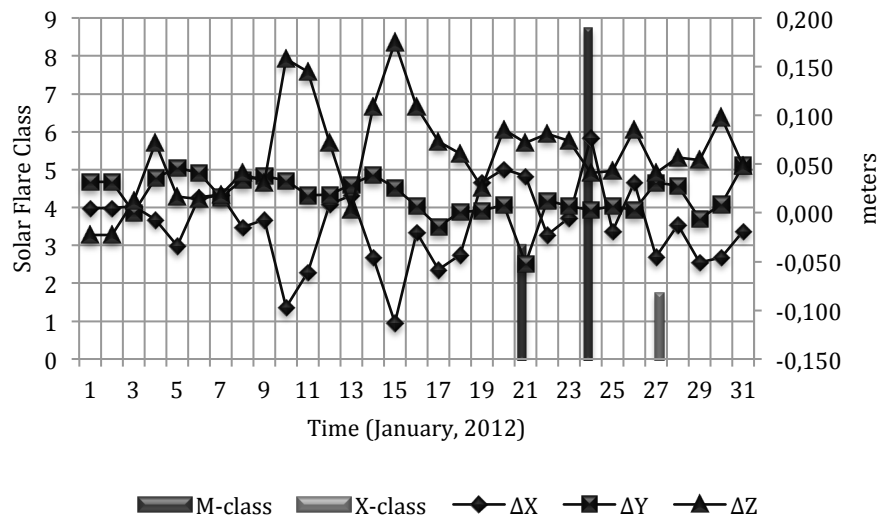


Fig. 4.30. dX, dY, dZ coordinates differences between Bodo and Andoya with respect to time

Figure 4.30 plots changes in differences of coordinates with respect to time. Also, compared with solar flare classification rating. The errors range: day 21 – ΔX – 0.038 meters; ΔY – 0.052 meters and ΔZ – 0.072 meters; day 24 – ΔX – 0.077 meters; ΔY – 0.003 meters; ΔZ – 0.041 meters. The errors range when no solar activity: ΔX – 0.045 meters; ΔY – 0.049 meters and ΔZ – 0.175 meters.

Figure 4.31 plots the represent the slope distance between Bergen and Stavanger, comparing with ionospheric index I95. Results indicate the baseline does not smooth with the values of the effect of ionosphere, as it is comparing baseline Vardo and Vardo Havn. Computed slope distance varies in -0.001–0.001 meters interval.

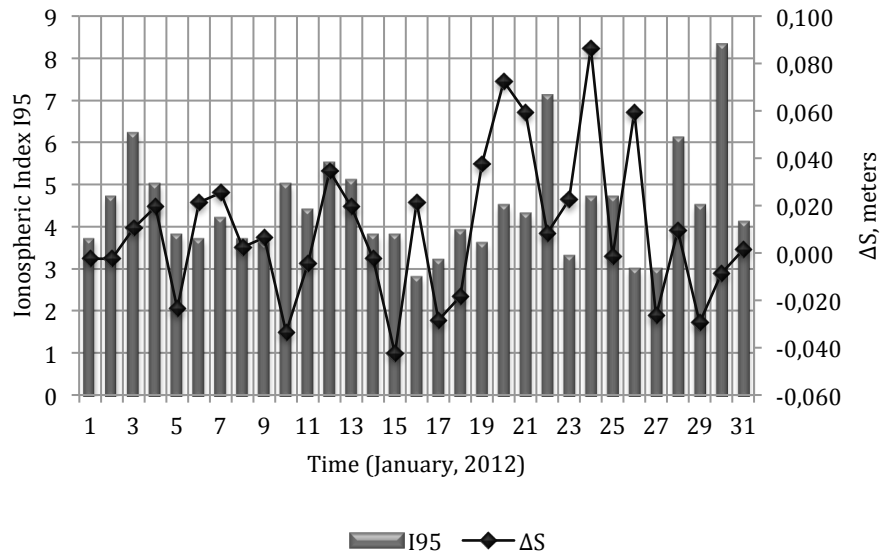


Fig. 4.31. Slope distance between Bodo and Andoya. Comparison with ionospheric activity index I95 for all investigated time period

Comparison of graphs, which show solar activity peaks on long-range vectors. The following mean repeatabilities comparing both chosen long range baselines were obtained: day 21 – ΔX – 0.005–0.038 meters; ΔY – 0.004– 0.052 meters; ΔZ – 0.027–0.072 meters; day 24 – ΔX – 0.077–0.176 meters; ΔY – 0.003– 0.367 meters; ΔZ – 0.041–0.105 meters When errors range in comparing “clean” days: ΔX – 0.042–0.045 meters; ΔY – 0.049– 0.054 meters; ΔZ – 0.112– 0.175 meters.

4.4. Influence of Global Navigation Satellite System Satellite Orbits Positions Definitions on Ground Positioning Coordinates

The estimation of the coordinate accuracy of single CPOS stations was performed using production of the broadcast navigation message. The quality of estimated coordinates of each CPOS stations were determined by post processing using Trimble Total Control software. Independent baselines (figure 4.32) were created from the stations of the CPOS network. Measures of X, Y and Z coordinates were recoded at 1-day interval. Computed coordinates of stations were compared with estimated values (table 4.1) and taking the differences. In doing so, processing strategy were developed which can improve the quality of global positioning system GPS-based position solution.

Table 4.1. CPOS stations from which tracing data is obtained

Station Name	Position		
	X, meters	Y, meters	Z, meters
Vardo - VARD	1839676.387	1109939.312	5985244.503
Vardo Havn - VARS	1844607.647	1109719.121	5983936.037
Kristiansand - KRSS	3348186.100	465040.853	5390738.088
Tregde - TGDE	3358081.176	445364.736	5386152.710
Longyarbyen - LYRS	1258602.259	346613.249	6222683.465
Svea - SVES	1284636.732	386010.924	6214635.574
Bergen - BRGS	3155871.428	290902.727	5516573.390
Stavanger - STAS	3275753.909	321110.866	5445041.896
Bodo – BOD3	2391774.544	615614.909	5860965.829
Andoya - ANDO	2175766.197	624248.094	5943417.668

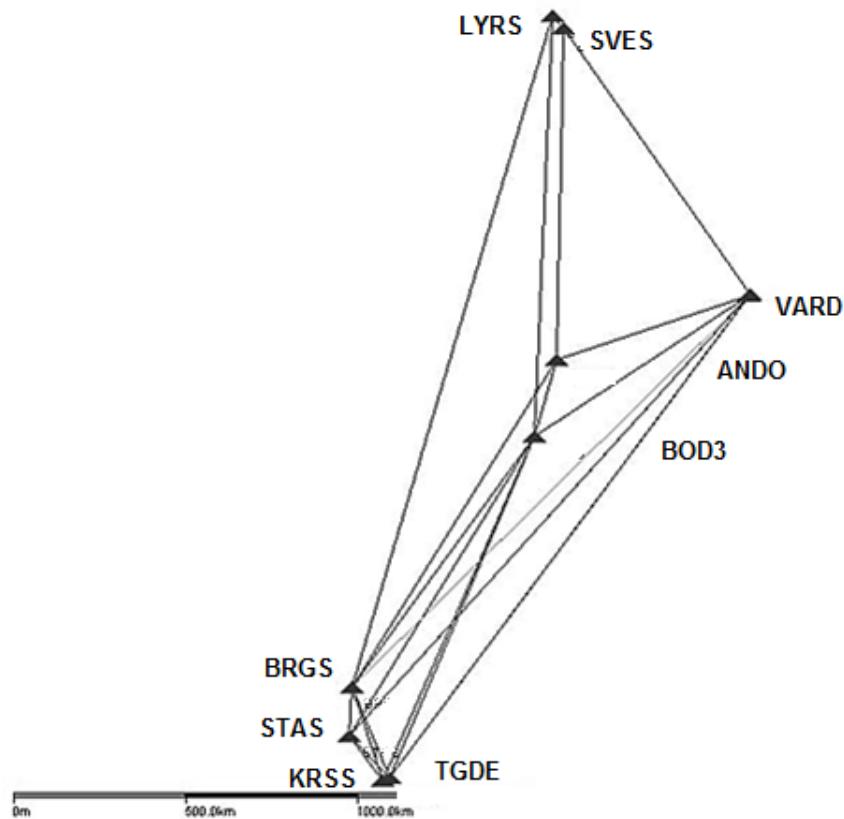


Fig. 4.32. The independent baselines used for GPS data processing in CPOS network

The main task of this process was to detect the influence that might be caused by solar storming on ground station position.

10 CPOS stations are chosen, all operated by the Norwegian Mapping Authority (NMA) and all are available with a precision of one centimetre. These stations have been used for computing positional vectors between selected pairs of CPOS stations.

The results of a number of test calculations show influence of Sun effect on geodetic coordinates of stations (Figs. 4.33–4.42).

Figure 4.33 plots the errors of the Andoya – ANDO station. These errors were computed by comparing estimated coordinates with computed coordinates using the Trimble Total Control software. The following mean repeatabilities comparing values were obtained: day 21 – ΔX – 6.8 millimetres; ΔY – 4.5 millimetres; ΔZ – 8.9 millimetres; day 24 – ΔX – 3.5 millimetres; ΔY – 2.6 millimetres; ΔZ – 2.7 millimetres. When errors range in comparing “clean” days: ΔX – 4.5 millimetres; ΔY – 4.1 millimetres; ΔZ – 6.6 millimetres.

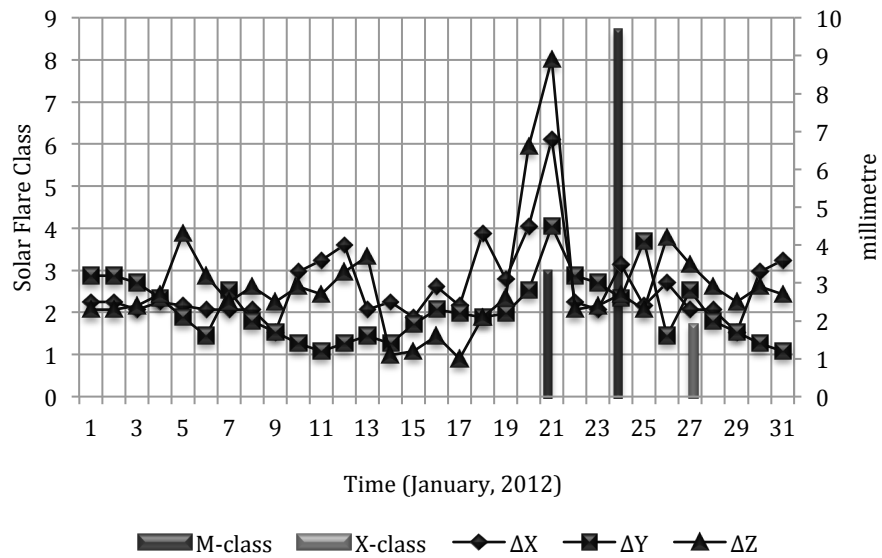


Fig. 4.33. The differences of the values of CPOS station - ANDO comparing with the respect to estimated coordinates

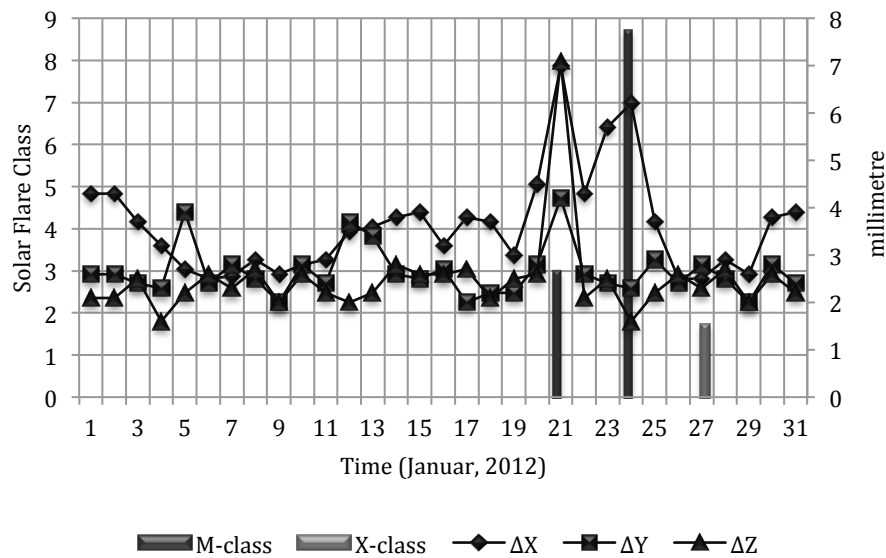


Fig. 4.34. The differences of the values of CPOS station – BOD3 comparing with the respect to estimated coordinates

Figure 4.34 plots the errors of the Bodo – BOD3 station. These errors were computed by comparing estimated coordinated with computed coordinated using the Trimble Total Control software. The following mean repeatabilities comparing values were obtained: day 21 – ΔX – 7 millimetres; ΔY – 4.2 millimetres; ΔZ – 7.1 millimetres; day 24 – ΔX – 6.2 millimetres; ΔY – 2.3 millimetres; ΔZ – 1.6 millimetres. When errors range in comparing “clean” days: ΔX – 5.7 millimetres; ΔY – 3.9 millimetres; ΔZ – 2.8 millimetres.

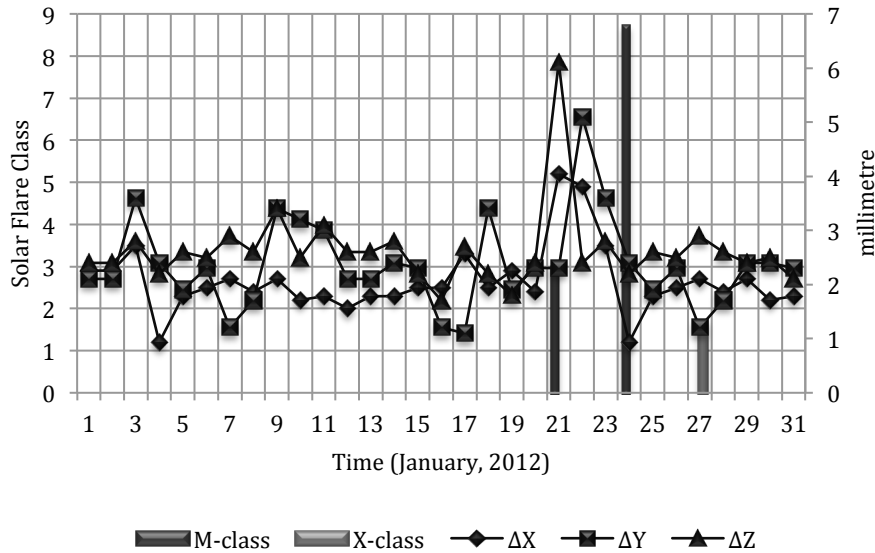


Fig. 4.35. The differences of the values of CPOS station – BRGS comparing with the respect to estimated coordinates

Figure 4.35 plots the errors of the Bergen – BRGS station. These errors were computed by comparing estimated coordinated with computed coordinated using the Trimble Total Control software. The following mean repeatabilities comparing values were obtained: day 21 – ΔX – 5 millimetres; ΔY – 2 millimetres; ΔZ – 6 millimetres; day 24 – ΔX – 1 millimetres; ΔY – 2 millimetres; ΔZ – 2 millimetres. When errors range in comparing “clean” days: ΔX – 4.9 millimetres; ΔY – 5.1 millimetres; ΔZ – 3.4 millimetres.

Errors of the Kristiansand – KRSS are plotted in figure 4.36 station. These errors were computed by comparing estimated coordinated with computed coordinated using the Trimble Total Control software. The following mean repeatabilities comparing values were obtained: day 21 – ΔX – 2.9 millimetres; ΔY – 0.5 millimetres; ΔZ – 2 millimetres; day 24 – ΔX – 5.1 millimetres; ΔY – 3.5 millimetres; ΔZ – 7.1 millimetres. When errors range in comparing “clean” days: ΔX – 5.3 millimetres; ΔY – 3.5 millimetres; ΔZ – 3.7 millimetres.

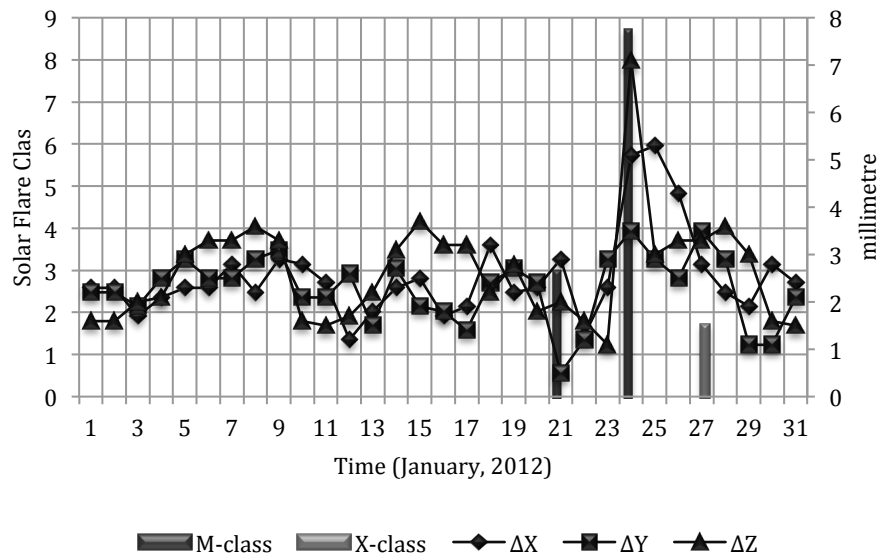


Fig. 4.36. The differences of the values of CPOS station – KRSS comparing with the respect to estimated coordinates

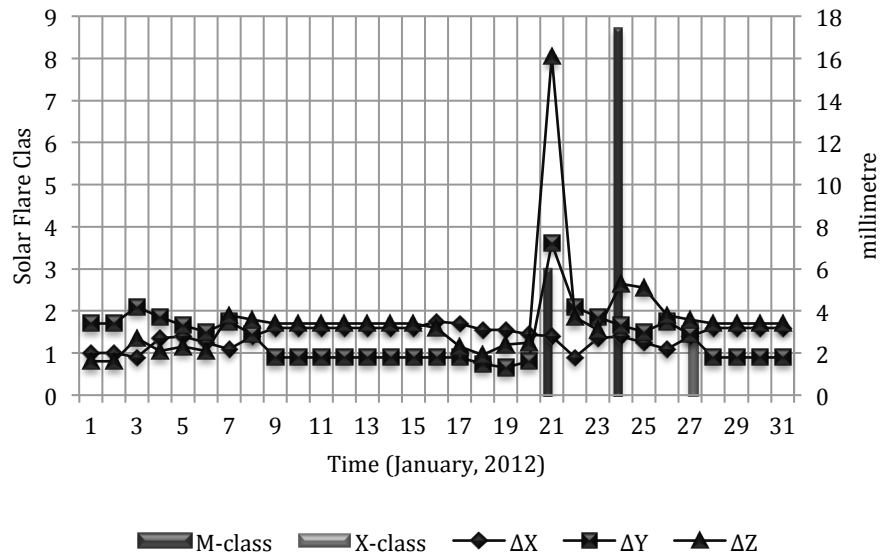


Fig. 4.37. The differences of the values of CPOS station – LYRS comparing with the respect to estimated coordinates

Figure 4.37 plots the errors of the Longyarbyen – LYRS station. These errors were computed by comparing estimated coordinated with computed coordinated using the Trimble Total Control software. The following mean repeatabilities comparing values were obtained: day 21 – ΔX – 2.8 millimetres; ΔY – 7.2 millimetres; ΔZ – 16.1 millimetres; day 24 – ΔX – 2.8 millimetres; ΔY – 3.3 millimetres; ΔZ – 5.3 millimetres. When errors range in comparing “clean” days: ΔX – 3.5 millimetres; ΔY – 4.2 millimetres; ΔZ – 5.1 millimetres.

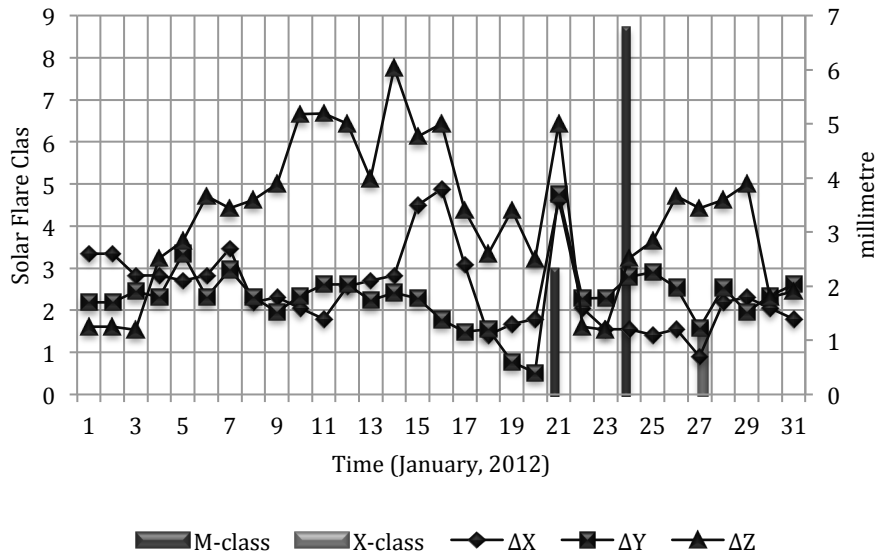


Fig. 4.38. The differences of the values of CPOS station – STAS comparing with the respect to estimated coordinates

Figure 4.38 plots the errors of the Stavanger – STAS station. These errors were computed by comparing estimated coordinated with computed coordinated using the Trimble Total Control software. The following mean repeatabilities comparing values were obtained: day 21 – ΔX – 3.6 millimetres; ΔY – 3.7 millimetres; ΔZ – 5 millimetres; day 24 – ΔX – 1.2 millimetres; ΔY – 2.2 millimetres; ΔZ – 2.5 millimetres. When errors range in comparing “clean” days: ΔX – 3.8 millimetres; ΔY – 2.6 millimetres; ΔZ – 6 millimetres.

Figure 4.39 plots the errors of the Svea – SVES station. These errors were computed by comparing estimated coordinated with computed coordinated using the Trimble Total Control software. The following mean repeatabilities comparing values were obtained: day 21 – ΔX – 1 millimetres; ΔY – 3.9 millimetres; ΔZ – 1.1 millimetres; day 24 – ΔX – 2 millimetres; ΔY – 2.6 millimetres; ΔZ – 1.7

millimetres. When errors range in comparing “clean” days: ΔX – 2.9 millimetres; ΔY – 4.9 millimetres; ΔZ – 2.7 millimetres.

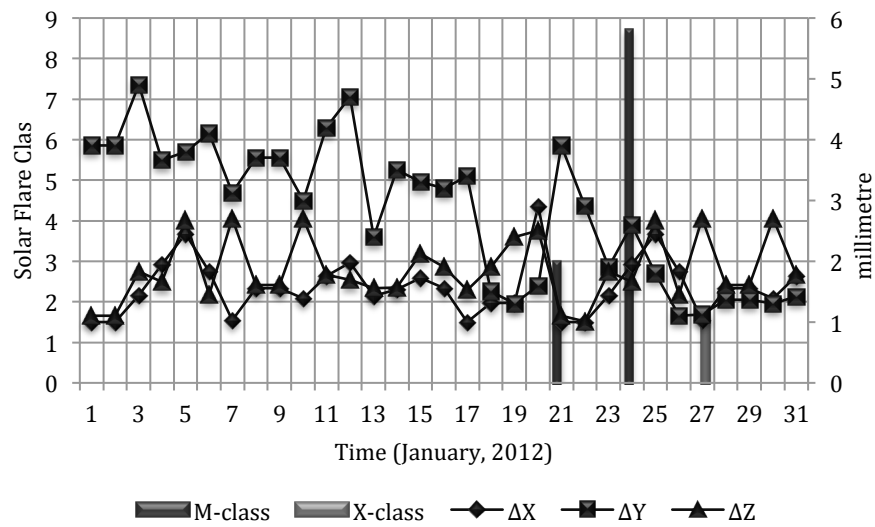


Fig. 4.39. The differences of the values of CPOS station – SVES comparing with the respect to estimated coordinates

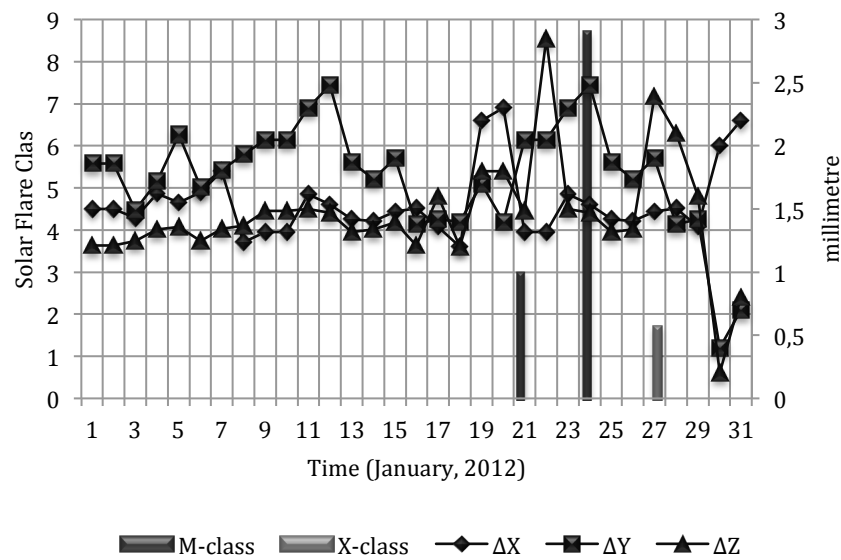


Fig. 4.40. The differences of the values of CPOS station – TGDE comparing with the respect to estimated coordinates

Figure 4.40 plots the errors of the Tregde – TGDE station. These errors were computed by comparing estimated coordinated with computed coordinated using the Trimble Total Control software. The following mean repeatabilities comparing values were obtained: day 21 – ΔX – 1.3 millimetres; ΔY – 2.1 millimetres; ΔZ – 1.5 millimetres; day 24 – ΔX – 1.5 millimetres; ΔY – 2.5 millimetres; ΔZ – 1.5 millimetres. When errors range in comparing “clean” days: ΔX – 2.3 millimetres; ΔY – 2.5 millimetres; ΔZ – 2.9 millimetres.

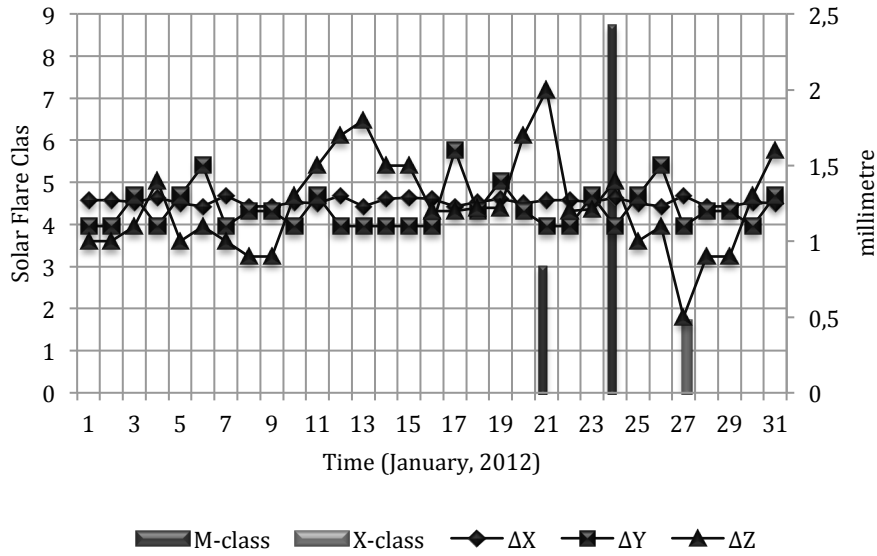


Fig. 4.41. The differences of the values of CPOS station – VARD comparing with the respect to estimated coordinates

Figure 4.41 plots the errors of the Vardo – VARD station. These errors were computed by comparing estimated coordinated with computed coordinated using the Trimble Total Control software. The following mean repeatabilities comparing values were obtained: day 21 – ΔX – 1.3 millimetres; ΔY – 1.1 millimetres; ΔZ – 2 millimetres; day 24 – ΔX – 1.3 millimetres; ΔY – 1.1 millimetres; ΔZ – 1.4 millimetres. When errors range in comparing “clean” days: ΔX – 1.3 millimetres; ΔY – 1.6 millimetres; ΔZ – 1.8 millimetres.

Figure 4.42 plots the errors of the Vardo Havn – VARS station. These errors were computed by comparing estimated coordinated with computed coordinated using the Trimble Total Control software. The following mean repeatabilities comparing values were obtained: day 21 – ΔX – 6.9 millimetres; ΔY – 5.5 millimetres; ΔZ – 7.6 millimetres; day 24 – ΔX – 3.7 millimetres; ΔY – 3.9

millimetres; ΔZ – 6.1 millimetres. When errors range in comparing “clean” days: ΔX – 4 millimetres; ΔY – 2.7 millimetres; ΔZ – 5.2 millimetres.

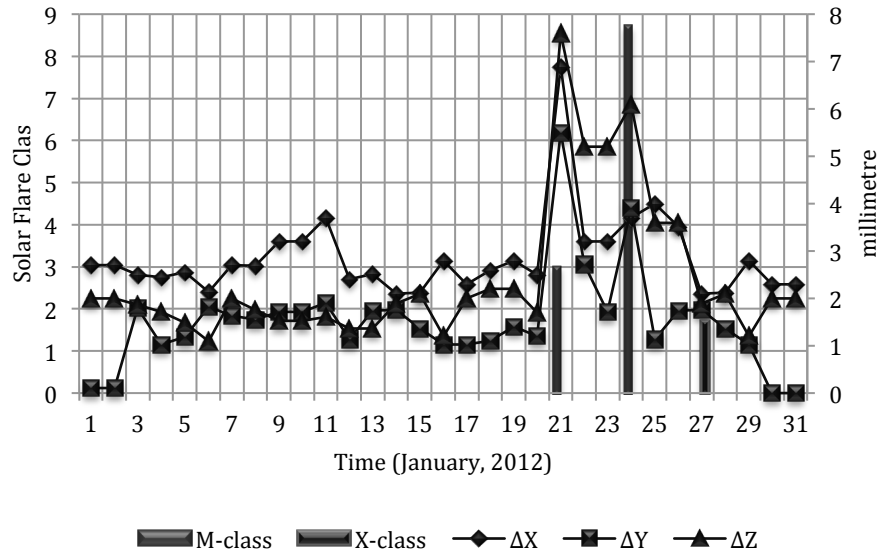


Fig. 4.42. The differences of the values of CPOS station – VARS comparing with the respect to estimated coordinates

The errors of the coordinates ranged about from 1 mm to 6 mm, whereas the errors in GPS coordinates when is reported Solar storm activity ranged from 2 mm to 16 mm. The mean differences between computed days and storming days significantly became larger.

4.5. Conclusions of Chapter 4

1. The coordinates of satellites were computed using the broadcast and precise ephemeris data files, and differences taken. Coordinates were computed for every 15 minutes throughout the selected periods in order to eliminate the risk of ephemeris interpolation errors.
2. Significant differences between two sets of coordinates were found – sometimes as much as hundred metres for individual satellites. It is suggested that these large differences might be due to residual errors in the predicted broadcast ephemerides, compounded by the unavoidable effects of “normal” (i.e. under non solar storming

conditions) space phenomena such as various forms of cosmic radiation pressures and gravity field fluctuations.

3. Daily values for the selected vectors were evaluated using commercial post-processing software, and the following conclusions were drawn: For the shorter vectors, the following mean repeatabilities were obtained: 0.016–0.047 meters. For medium distance vectors: 0.057–0.794 meters. For long distance vectors: 0.052–0.367 meters
4. The quality of computed geodetic coordinates of each CPOS station ranged from 1 mm to 6 mm, whereas the errors in GPS coordinates when is reported Solar storm activity ranged from 2 mm to 16 mm.
5. When comparing day-to-day vector results at all three distances classes, some correlation was seen between large differences and M-class storming. However, it was not possible to see that an M-class storm would reliably guarantee a large vector error.
6. Meanwhile, judging from these results, solar storming would only appear to be a concern at mid and longer distances. In other words, the average survey user at shorter distances probably need not worry about solar events.
7. Meanwhile, there would appear to be more reliable evidence of differences between day and night observations. This is somewhat unexpected, since some of the night observations will nevertheless have passed through the daylight ionosphere.

General Conclusions

Detailed conclusions have already been presented in each of the forgoing chapters. These have led to the following general conclusions at the end of this study.

The goal of this thesis was to examine whether the error in satellites' orbital locations due to solar activity can affect the accuracy of the positions detected by ground receivers, including consideration of the effects of satellites in Earth shadow:

1. The solar storming events influence on the satellites coordinates is impossible to distinguish by the comparison of the broadcast and precise ephemerides. Significant differences between two sets of satellites coordinates – broadcast and precise – were found. But it is suggested that these large differences might be due to residual errors in the predicted broadcast ephemerides, compounded by the unavoidable effects of “normal” (i.e. under non solar storming conditions) space phenomena such as various forms of cosmic radiation pressures and gravity field fluctuations.
2. The solar storming events have influence to the accuracy of the ground positioning vectors. The errors range approximately till 50 mm for the short vectors, and up to 800 mm for the mid and long vectors.

3. The effect of Earth's shadowing on a satellite positioning is not significant, because the differences of ephemerides of satellites passing the Earth's shadow do not show changes. Also, evaluations show that there are just one or two satellites in Earth's shadow at the same time.
4. The solar storming events have influence to the accuracy of the geodetic coordinates of the points on the Earth's surface. For example, the quality of computed geodetic coordinates of some CPOS station ranged from 1 mm to 6 mm, whereas the errors in geodetic coordinates when is reported Solar storm activity ranged from 2 mm to 16 mm.

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Annexes

Annex A. Source Code of Conversion from Civil Date to GPS Week and Seconds-in-Week

```
'Program "Datecomp_3.bas" to compute from calender date to DoY, week, week cycle
'and seconds-in-week
'GP February 2007
'Version 3

Inputdate:
input "Date dd,mm,yyyy....."; dom%,mon%,anno%
if anno%<1900 then cls:print "Enter the year in full and try again":print:goto
Inputdate
Inputtime:
if mon%>12 then mon%=mon%-12:anno%=anno%+1
Input "Epoch time in UT hh,mm,ss.ssss (use "." for decimal point)....";
hh%,mm%,ss#
print
print " Date           Epoch time      CN   GPSW   GLOW   Day       Sec-in-W"
print dom%;". ";mon%;". ";anno%;" ";
print hh%;". ";mm%;". ";
print using "##.###";ss#;" ";
print #1,using "##";dom%;
print #1,".";
print #1,using "##";mon%;
print #1,".";
print #1,using "###";anno%;
print #1,".";
print #1,using "##";hh%;
print #1,".";
print #1,using "##";mm%;
print #1,".";
print #1, using "##.###";ss#;" ";
'Following are variables introduced:
' mon%           number of the mon
```

```

' dom%           day of the monthth
' anno%          year
' hh%            epoch hours
' mm%            epoch minutes
' ss#            epoch seconds using fullstop as decimal

'Intermediate parameters:
if mon%<3 then anno%=anno%-1:mon%=mon%+12

'Julian Date:
UT#=hh%+(mm%/60)+(ss#/3600)
'if UT#=0 then UT#=UT#+24
JD#=int(365.25*anno%)+int(30.6001*(mon%+1))+dom%+UT#/24+1720981.5
'print:print "Julian Date is ";
'print using "#####.#####";JD#:print

'week number:
'Following are variables introduced:
' GPSweekcycle% Cycle number in the GPS week cycle system
' weekgl%        number of weeks from the GNSS start date
'                (also equal to the GLONASS week number)
' WEEKgp%        the actual GPS week number corrected for cycle
GPSweekcycle%=1
weekgl%=int((JD#-2444244.5)/7)
'print "GLONASS Week Number is ";week%
if weekgl%>1024 then WEEKgp%=weekgl%-1024:GPSweekcycle%=GPSweekcycle%+1 else goto weekout
weekout:
weekin:
if WEEKgp%>1024 then WEEKgp%=WEEKgp%-1024:GPSweekcycle%=GPSweekcycle%+1:goto weekin
weekout:
'print "GPS Week Number is ";WEEK%; " in GPS Week Cycle Number ";GPSweekcycle%
print " ";GPSweekcycle%; " ";WEEKgp%; " ";weekgl%; " ";
print #1, " ";GPSweekcycle%;space$(4);WEEKgp%;space$(4);weekgl%;space$(4);

'Day of the week:
'Following are variables introduced:
' ENN%           the conventional day number counter known as "N"
' dayname$       the name of the day as computed
'Following line necessary to handle exactly midnight - int algorithm!!
if hh%=0 and mm%=0 and ss#=0 then JD#=JD#+0.0000005
ENN%=int(7*((JD#+0.5)/7-int((JD#+0.5)/7)))
if ENN%=0 then dayname$="Monday "
if ENN%=1 then dayname$="Tuesday "
if ENN%=2 then dayname$="Wednesday"
if ENN%=3 then dayname$="Thursday "
if ENN%=4 then dayname$="Friday "
if ENN%=5 then dayname$="Saturday "
if ENN%=6 then dayname$="Sunday "
print dayname$; " ";
print #1,tab(5);dayname$;

'Seconds-in-week:
'Following are variables introduced:
' SinDay#        number of seconds in the day up to the selected epoch
' Siw#           number of seconds in the week up to the selected epoch
SinDay#=(hh%*3600)+(mm%*60)+ss#
if ENN%=6 then Siw#=SinDay#:goto finished
for i%=1 to 6
    if i%=ENN%+1 then Siw#=SinDay#+(86400*i%)
next
finished:
'print "Seconds-in-Week is ";;print using "#####.#####";Siw#
print using "#####.#####";Siw#
print':print "Julian Date is ";
print using "Julian Date is #####.##### ";JD#:print using "Week day number is
#";ENN#:print
print #1, using "#####.#####";Siw#
print
input"Compute another Epoch? Y/N (y/n)"; repeat$
if repeat$="N" or repeat$="n" then goto finished2
print
input"Same date again? Y/N (y/n)"; repeat$
if repeat$="Y" or repeat$="y" then print:goto Inputtime:
goto inputdate

```

```
finished2:
print
print "Program completed. Print results from file secinweek.txt."
PRINT #1,
PRINT #1,
PRINT #1,"Program ended."
PRINT #1,
PRINT #1,
PRINT #1,
PRINT #1,"Output to file ";outfile$
close
sleep
```

Annex B. Source Code of Counting GPS Navigation Message

```
'PROGRAM "Navmesscounting-4.bas" FOR COUNTING GPS NAVMESSAGE TOE'S
'Puts the nav message data into arrays.

'Start the timer clock
nowed=timer
print "working":print
dim navmess(1 to 32,0 to 12,1 to 20) as double
dim navcount(1 to 32) as single
for i%=1 to 32
    navcount(i%)=0
next

'Set up the files
inputnavfile$="c:\Test-krss0020\krss0020 modified.txt"
outputfile$=left$(inputnavfile$,len(inputnavfile$)-4)+" navmes-1.txt"
open inputnavfile$ for input as #1
open outputfile$ for output as #2

'Set up counters
icount%=1
outpnt%=0

do
'Get past the header and sort out the spacing
    gosub headspace
'Decode the incoming nav message only for sat no and toe and put to navmes-1 file
    gosub decode-lite
loopout:
loop until eof(1)

print "Decoding done":print
'At this point, we have all the nav parameters for all the registered epochs
'from the nav file in a long data string, filed with commas.
close

outputfile$=left$(inputnavfile$,len(inputnavfile$)-4)+" navmes-1.txt"
newoutfile1$=left$(inputnavfile$,len(inputnavfile$)-4)+" navmes-count.txt"
newoutfile1test$=left$(inputnavfile$,len(inputnavfile$)-4)+" navmes-counttest.txt"
newoutfile2$=left$(inputnavfile$,len(inputnavfile$)-4)+" navmes-toe-s.txt"
open outputfile$ for input as #2
open newoutfile1$ for output as #3
open newoutfile1test$ for output as #33
open newoutfile2$ for output as #4
do
    input
    #2,satno%,af0#,af1#,af2#,Crs#,Deltan#,Mnaught#,Cuc#,e#,Cus#,RootA#,toe#,Cic#,OMEGA0#
    ,Cis#,i0#,Crc#,omega#,omegadot#,idot#
    print
    satno%,af0#,af1#,af2#,Crs#,Deltan#,Mnaught#,Cuc#,e#,Cus#,RootA#,toe#,Cic#,OMEGA0#,Ci
    s#,i0#,Crc#,omega#,omegadot#,idot#
    print satno%,toe#
    if satno%=0 then goto programended
    if toe%=0 then toe#=604800
    if navmess(satno%,0,0)=0 then
        navmess(satno%,0,0)=toe#
        navmess(satno%,1,0)=toe#
        gosub firstarray
        navcount(satno%)=navcount(satno%)+1
    end if
    print "yes1 ",
    if toe#≠navmess(satno%,0,0) then
        print "yes2 ",
        goto loopended
    else
        navmess(satno%,0,0)=toe#
        navcount(satno%)=navcount(satno%)+1
        navmess(satno%,navcount(satno%),0)=toe#
        gosub newarray
        ' *****
```

```

'      print "yes3"
'      end if
loopended:
loop until eof(2)

programended:
'Now put to file the arrays:
for i%=1 to 32
  print #3,navcount(i%)
  print #33,"sat no ";i%,navcount(i%)
  for j%=0 to 12
    for k%=1 to 20 '*****
      print #4,navmess(i%,j%,k%)
    next
  next
next
print "Arrays put to file":print
'for i%=1 to 32
'  print "sat ";i%;" ";
'  for j%=0 to 12
'    print using "##### ";navmess(i%,j%,19);navmess(i%,j%,0)
'  next
'  print
'next

print
' Now we are successfully reading in the file into the various parameters.
'Next is to put them into the arrays.

'Stop the run time clock
ended=timer
print "Runtime: ";print using "+#.####^ seconds";(ended-nowed)/1000
print "All done!"
close
sleep

'=====
'END OF EXECUTABLE PART OF PROGRAM
'=====

firstarray:
  navmess(satno%,1,1)=Mnaught#
  navmess(satno%,1,2)=Deltan#
  navmess(satno%,1,3)=e#
  navmess(satno%,1,4)=RootA#
  navmess(satno%,1,5)=OMEGA0#
  navmess(satno%,1,6)=i0#
  navmess(satno%,1,7)=omega#
  navmess(satno%,1,8)=omegadot#
  navmess(satno%,1,9)=idot#
  navmess(satno%,1,10)=Cuc#
  navmess(satno%,1,11)=Cus#
  navmess(satno%,1,12)=Crc#
  navmess(satno%,1,13)=Crs#
  navmess(satno%,1,14)=Cic#
  navmess(satno%,1,15)=Cis#
  navmess(satno%,1,16)=af0#
  navmess(satno%,1,17)=af1#
  navmess(satno%,1,18)=af2#
  navmess(satno%,1,19)=satno%
return

newarray:
  navmess(satno%,navcount(satno%),1)=Mnaught#
  navmess(satno%,navcount(satno%),2)=Deltan#
  navmess(satno%,navcount(satno%),3)=e#
  navmess(satno%,navcount(satno%),4)=RootA#
  navmess(satno%,navcount(satno%),5)=OMEGA0#
  navmess(satno%,navcount(satno%),6)=i0#
  navmess(satno%,navcount(satno%),7)=omega#
  navmess(satno%,navcount(satno%),8)=omegadot#
  navmess(satno%,navcount(satno%),9)=idot#
  navmess(satno%,navcount(satno%),10)=Cuc#
  navmess(satno%,navcount(satno%),11)=Cus#
  navmess(satno%,navcount(satno%),12)=Crc#

```

```

navmess(satno%,navcount(satno%),13)=Crs#
navmess(satno%,navcount(satno%),14)=Cic#
navmess(satno%,navcount(satno%),15)=Cis#
navmess(satno%,navcount(satno%),16)=af0#
navmess(satno%,navcount(satno%),17)=af1#
navmess(satno%,navcount(satno%),18)=af2#
navmess(satno%,navcount(satno%),19)=satno%
return

headspace:
'Get past the nav file header
input #1,a$
if left$(a$,13)="END OF HEADER" then
    outpnt%=1
end if
if outpnt%=0 then goto loopout
if outpnt%=1 and left$(a$,13)="END OF HEADER" then goto loopout
for l%=(len(a$)-5) to 1 step -1
    if mid$(a$,l%,1)="E" then
        a$=left$(a$,l%+3)+" "+right$(a$, (len(a$)-l%-3))
        l%=l%-2
    end if
next
'Sort out the tabular spacing
if left$(a$,1)<>"-" then a$=" "+a$
if mid$(a$,24,1)=" " then a$=left$(a$,23)+" "+right$(a$, (len(a$)-23))
if mid$(a$,24,1)="-" then a$=left$(a$,23)+" "+right$(a$, (len(a$)-23))
if icount%=1 then jcount%=1
return

decode_lite:
if jcount%=9 then
    jcount%=1
end if
'Navdata block lines 8 and 7 decoding
if jcount%=8 or jcount%=7 then
    jcount%=jcount%+1
    goto icountup1
end if
'Navdata block line 6 decoding
if jcount%=6 then
    idot#=val(left$(a$,20))
    print #2,idot#
    '
    jcount%=jcount%+1
end if
'Navdata block line 5 decoding
if jcount%=5 then
    i0#=val(left$(a$,20))
    crc#=val(mid$(a$,21,20))
    omega#=val(mid$(a$,41,20))
    omegadot#=val(mid$(a$,61,20))
    print #2,i0#,crc#,omega#,omegadot#,
    jcount%=jcount%+1
end if
'Navdata block line 4 decoding
if jcount%=4 then
    toe#=val(left$(a$,20))
    Cic#=val(mid$(a$,21,20))
    OMEGA0#=val(mid$(a$,41,20))
    Cis#=val(mid$(a$,61,20))
    print #2,toe#,Cic#,OMEGA0#,Cis#,
    jcount%=jcount%+1
end if
'Navdata block line 3 decoding
if jcount%=3 then
    Cuc#=val(left$(a$,20))
    e#=val(mid$(a$,21,20))
    Cus#=val(mid$(a$,41,20))
    RootA#=val(mid$(a$,61,20))
    print #2,Cuc#,e#,Cus#,RootA#,
    jcount%=jcount%+1

```

```
        end if
'Navdata block line 2 decoding
    if jcount%=2 then
        Crs#=val(mid$(a$,21,20))
        Deltan#=val(mid$(a$,41,20))
        Mnaught#=val(mid$(a$,61,20))
        print #2,Crs#,Deltan#,Mnaught#,
        jcount%=jcount%+1
    end if
'Navdata block line 1 decoding
    if jcount%=1 then
        if val(left$(a$,3))<10 then a$=" "+a$
        satno%=val(left$(a$,4))
        navtime$=(mid$(a$,5,19))
        af0#=val(mid$(a$,24,20))
        af1#=val(mid$(a$,44,21))
        af2#=val(mid$(a$,64,21))
        print #2,satno%,af0#,af1#,af2#,
        jcount%=jcount%+1
    end if
icountup1:
    icount%=icount%+1
return
```

Annex C. Source Code to Extract the Navigation data

```
'Extracts the nav data and the sp3 data and combines into single records
'for every 15 minutes.
'Produces combined nav/sp3 plus differences file (#9)
'Modified to include test for when nav epoch is less than sp3 epoch

'Screen shows a count of matched epochs for each satellite. Most satellites
'have 1 or more whole-15 minute epochs missing in the lsecdt file, but the
'program takes care of this by just not recording that whole-15 minute epoch!

'GP
'Version 25.06.2012

nowed=timer

print "Working..."
print

navin$="c:\0-George\2010-11\Vilnius    May    2011\Air    paper\Test-dgls0380\dgls0380
modified 24hlsecdt.txt"
sp3in$="c:\0-George\2010-11\Vilnius    May    2011\Air    paper\Test-
dgls0380\igs16742+mod24hl5mindt.txt"
combineout$=left$(navin$,len(navin$)-4)+"_igscomb15min.txt"

open navin$ for input as #1
open sp3in$ for input as #2
open combineout$ for output as #9

matched%=0
do until eof(1)
    input #1,satnon%,epochn%,xn#,yn#,zn#,tn$
input2:
    input #2,satno3%,epoch3%,x3#,y3#,z3#,t3$
    'TESTING FOR EQUAL SAT NOS
    if satnon%>satno3% then
        print matched%," matched epochs for satellite ";satno3%;print
        matched%=0
        do until satno3%=satnon%
            input #2,satno3%,epoch3%,x3#,y3#,z3#,t3$
            loop
        print "SAT NO FILES MATCHED FOR SATELLITE ";satnon%
    end if
    'TESTING EQUAL EPOCHS IN THE TWO FILES
    if epochn%<epoch3% then
        'RUN THROUGH THE NAV FILE AS LONG AS NAV EPOCH IS LESS THAN sp3 EPOCH
        do while epochn%<epoch3%
            input #1,satnon%,epochn%,xn#,yn#,zn#,tn$
            loop
        end if
        'IF NOW THE NAV EPOCH IS GREATER THAN THE sp3 EPOCH
        'BECAUSE THERE IS A NAV EPOCH MISSING (FOR WHATEVER REASON) THEN INPUT
        'THE NEXT sp3 EPOCH BY JUMPING BACK UP TO LABEL 'input2'
    if epochn%>epoch3% then
        matched%=0
        goto input2
    end if

    'NOW OUTPUT THE MATCHED RECORD WITH BOTH NAV AND sp3 DATA TO FILE
    matched%=matched%+1
    tn#=val(tn$):t3#=val(t3$)
    dx#=(xn#-x3#):dy#=(yn#-y3#):dz#=(zn#-z3#):td#=(tn#-t3#):td$=str$(td#)
    print #9,satnon%,satno3%,epochn%,epoch3%,
    print #9,using " #####.### ";xn#,yn#,zn#,
    print #9,using " +.#####^";tn#,
    print #9,using " #####.### ";x3#,y3#,z3#,
    print #9,using " +.#####^";t3#,
    print #9,using " +.#####^";dx#,dy#,dz#,
    print #9,td$
inext:
loop
```

```
ENDIT:
ended=timer
print "Runtime: ";:print using "+#.####^ ^ ^ ^ seconds";(int((ended-nowed)*1000))/1000
print "All done!"
close
sleep
```

Annex D. Source Code for Computing Satellite in Earth's Shadow for a Given Date

'Program <Sateclipse 20120507.bas> to compute satellite eclipse for a given date.
'Modified from <Sateclipse 20110105 sunlong change.bas> 07.05.2012 to handle only GPS

'WORKS ONLY FOR LEAP YEAR!!!!!!!!!!!!!!!!!!!!!!

```
Print "(Program Sateclipse 20120507)"
print
CONST PI AS DOUBLE = 3.1415926535897932
'Ellipsoid parameters
a#=6378137
esq#=0.00669437999013
umbangletan#=((1392000-6378)/149597890)
penumbangletan#=((1392000+6378)/149597890)

startinput:
'input "Input path to data files          ";datapath$
'input "Input own position: Latitude  D,M,S,S ";latdeg%,latmin%,latsec#
'input "Input own position: Longitude D,M,S,S ";londeg%,lonmin%,lonsec#
input "Input required date DD,MM,YYYY (use zeros to fill)";reqday$,reqmon$,reqyear$

filereqdate$=reqyear$+reqmon$+reqday$
DoY%=val(reqday$)
reqmon%=val(reqmon$)
if reqmon%=2 then DoY%=DoY%+31 'date +31
if reqmon%=3 then DoY%=DoY%+60 'date +31+29
if reqmon%=4 then DoY%=DoY%+91 'date +31+29+31
if reqmon%=5 then DoY%=DoY%+121 'date +31+29+31+30
if reqmon%=6 then DoY%=DoY%+152 'date +31+29+31+30+31
if reqmon%=7 then DoY%=DoY%+182 'date +31+29+31+30+31+30
if reqmon%=8 then DoY%=DoY%+213 'date +31+29+31+30+31+30+31
if reqmon%=9 then DoY%=DoY%+244 'date +31+29+31+30+31+30+31+31
if reqmon%=10 then DoY%=DoY%+274 'date +31+29+31+30+31+30+31+31+30
if reqmon%=11 then DoY%=DoY%+305 'date +31+29+31+30+31+30+31+31+30+31
if reqmon%=12 then DoY%=DoY%+335 'date +31+29+31+30+31+30+31+31+30+31+30
DoY%=str$(DoY%)
if DoY%<100 then DoY$="0"+DoY$
if DoY%<10 then DoY$="0"+DoY$

'input "Input required Mask Angle D          ";mask%
input "sp3 number                          ";sp3no$
sp3gps$="igs"+sp3no$+".sp3"
'sp3glonass$="igl"+sp3no$+".sp3"*****
'input "Input GPS sp3 file name              ";sp3gps$
'input "Input GLONASS sp3 file name          ";sp3glonass$
'input "Input solar polynomials file name    ";Polynomials$
Polynomials$="sarsun12.dat"

utdatapath$="c:\0-George\2010-11\vilnius May 2011\Eclipse paper\sp3 files\2012\"
indatapath$="c:\0-George\2010-11\vilnius May 2011\Eclipse paper\sp3 files\2012\"
latdeg%=60
latmin%=39
latsec#=4.8
londeg%=10
lonmin%=55
lonsec#=42.4
mask%=15
mask#=mask%*PI/180
pointlatdeg#=(latdeg%+latmin%/60+latsec#/3600)
pointlondeg#=(londeg%+lonmin%/60+lonsec#/3600)
pointlatrad#=(latdeg%+latmin%/60+latsec#/3600)*PI/180
pointlonrad#=(londeg%+lonmin%/60+lonsec#/3600)*PI/180
'reqdate$="09-09-2010"

sp3gps$=indatapath$+sp3gps$
sp3glonass$=indatapath$+sp3glonass$
Polynomials$=indatapath$+Polynomials$
plan$=utdatapath$+"Sateclipse "+filereqdate$+".ec1"
```

[illegible]

```

for i%=1 to 35
    print outline(i%)
    print #9, outline(i%)

next
print #9,
print #9,chr$(94);" = visible; @ = in eclipse; x = in penumbra"
print #9,
print #9,"(Run by program 'sateclipse 20120507.bas' on ";date$;)"

goto progend

available:
input #2, a$
    if left$(a$,1)="" then
        'print datestring$:print a$
        y%=val(mid$(a$,4,4))
        mnth%=val(mid$(a$,9,2))
        d%=val(mid$(a$,12,2))
        h%=val(mid$(a$,15,2))
        m%=val(mid$(a$,18,2))
        s%=val(mid$(a$,21,4))
        sod%=h%*3600+m%*60+s#
    end if
    if left$(a$,1)="P" or left$(a$,2)="PR" then
        if left$(a$,2)="PG" or left$(a$,2)="PR" then
            bird%=val(mid$(a$,3,2))
            if left$(a$,2)="PR" then bird%=bird%+35:end if
            print left$(a$,4);" ";bird%;" ";
            satx#=val(mid$(a$,6,13))*1000
            saty#=val(mid$(a$,20,13))*1000
            satz#=val(mid$(a$,34,13))*1000
            if left$(a$,2)="PR" then bird%=bird%+35

            Now compute the sub-shadow point lat and long
            x#=(d%+(h%+m%/60+s#/3600)/24)/32
            RequTH#=(h%+m%/60+s#/3600)

Dec#=-eph(12%,4)+eph(12%,5)*x#+eph(12%,6)*x#^2+eph(12%,7)*x#^3+eph(12%,8)*x#^4
E#=-eph(12%,9)+eph(12%,10)*x#+eph(12%,11)*x#^2+eph(12%,12)*x#^3+eph(12%,13)*x#^4
'Get sub-Sun point
sunlat#=-Dec#
sunlon#=(24-E#-RequTH#)*15
sunlon#=- (RequTH#*15-180)
'Get sub-Shadow point
shalat#=-sunlat#
if sunlon#>0 then
    shalon#=-sunlon#-180
else
    shalon#=-sunlon#+180
end if

shalatrad#=-shalat#*pi/180
shalonrad#=-shalon#*pi/180

'Get longitude of subsat point
satlonrad#=atn(satz#/satx#)
if satx#>=0 and saty#>=0 then satlonrad#=satlonrad#:qu%=1 '1st quadrant
if satx#<0 and saty#>=0 then satlonrad#=PI+satlonrad#:qu%=2 '2nd quadrant
if satx#<0 and saty#<0 then satlonrad#=PI+satlonrad#:qu%=3 '3rd quadrant
if satx#>=0 and saty#<0 then satlonrad#=2*PI+satlonrad#:qu%=4 '4th quadrant
'satlon is now measured full circle eastwards
satlondeg#=satlonrad#*180/PI

'Get latitude of subsat point
latrad#=atn(satz#/sqr((satx#^2)+(saty#^2)))
for i%=1 to 10
    new#=a#/sqr(1-esq#*(SIN(latrad#))^2)
    latrad#=atn((satz#+esq#*new#*SIN(latrad#))/sqr(satx#^2+saty#^2))
next
'print using "## #####.### #####.### #####.### # ###.###
###.###";bird%,satx%,saty%,satz%,qu%,satlondeg#,latrad#*180/PI;

```

```

'Get arc length from point to subsat point - spherical cosine rule
cosarcrad#=(sin(pointlatrad#)*sin(latrad#)+cos(pointlatrad#)*cos(latrad#)*cos(abs(sa
tlonrad#-pointlonrad#)))
arcdeg#=(acos(cosarcrad#)*180/PI

'And now the spherical sine rule for the azimuth
sinarcrad#=(1-cosarcrad#^2)
sinazrad#=(cos(latrad#)*SIN(abs(satlonrad#-pointlonrad#)))/sinarcrad#
azrad#=(asin(sinazrad#)

'Test to get into the right quadrant
if satlonrad#>pointlonrad# and pointlatrad#>latrad# then azrad#=pi-azrad#
if satlonrad#<pointlonrad# and pointlatrad#>latrad# then azrad#=pi+azrad#
if satlonrad#<pointlonrad# and pointlatrad#<latrad# then azrad#=2*pi-azrad#
''print using "\ \ Azimuth deg +###.#####";a$,azrad#*180/PI

'Finally to get elevation to satellite
'NB Converting to xyz using spherical 6378137 radius!!!!
pointx#=a#*cos(pointlatrad#)*cos(pointlonrad#)
pointy#=a#*cos(pointlatrad#)*sin(pointlonrad#)
pointz#=a#*sin(pointlatrad#)
pointvec2#=((pointx#^2)+(pointy#^2)+(pointz#^2))
pointvec#=(sqrt((pointx#^2)+(pointy#^2)+(pointz#^2))
satvec#=(sqrt(satx#^2+saty#^2+satz#^2))
arcrad#=(acos(cosarcrad#)
satrange#=(sqrt((pointvec#^2+satvec#^2-2*pointvec#*satvec#*cosarcrad#)
satanglerad#=(asin(sinarcrad#*pointvec#/satrange#)
if satvec#>=satrange# then extanglerad#=(satanglerad#+asin(sinarcrad#)
if satvec#<satrange# then extanglerad#=(satanglerad#+PI-asin(sinarcrad#)
elevrad#=(PI/2-extanglerad#

'print using " ###.#";elevrad#*180/PI
'print #9, bird%::print #9, using " #####.### #####.###
#####.###";satx#,saty#,satz#
'print #9, bird%::print #9, using "###.### ###.### ###.### ###.###
#####"; latrad#*180/PI,satlondeg#,arcdeg#,azrad#*180/PI,elevrad#*180/PI
'print bird%, elevrad#*180/PI

'The next few lines insert visibility based on coords that are in the program
earlier on.
=====
'if left$(a$,2)="PG" then
' if elevrad#>(mask#) then mid$(outline(bird%+3),(6+sod%/900))=chr$(94)
'end if
'if left$(a$,2)="PR" then
' if elevrad#>(mask#) then mid$(outline(bird%+35),(6+sod%/900))=chr$(94)
'end if

'Now get the eclipse data
satx#=satx#/1000
saty#=saty#/1000
satz#=satz#/1000
' Get radius to satellite
satradius#=(sqrt(satx#^2+saty#^2+satz#^2))
satalt#=(saturadius#-a#)/1000 'km
' Now get xyz of shadow centre using spherical Earth radius 6378.137 km
shadx#=(saturadius#*cos(shalatrads#)*cos(shalonrad#)
shady#=(saturadius#*cos(shalatrads#)*sin(shalonrad#)
shadz#=(saturadius#*sin(shalatrads#)
' And the shadow radii
umbrad#=(a#/1000-saturadius#*umbangletan#
penumbrad#=(a#/1000+saturadius#*umbangletan#
' And then distance from shadow centre to satellite
Satdist#=(sqrt((satx#-shadx#)^2+(saty#-shady#)^2+(satz#-shadz#)^2)
'print saturadius#,umbrad#,satdist#
' if satdist#<umbrad# and elevrad#>(mask#) then
mid$(outline(bird%+3),(6+sod%/900))="@
' if satdist#>umbrad# and satdist#<penumbrad# and elevrad#>(mask#) then
mid$(outline(bird%+3),(6+sod%/900))="x"
' if satdist#<umbrad# then mid$(outline(bird%+3),(6+sod%/900))="E"

```

```
end if  
return
```

```
progend:  
print  
print "Finished"  
close  
print  
input "More Y/N?"; runagain$  
If runagain$= "Y" or runagain$= "y" then goto startinput  
sleep
```

Annex E. Figures of Broadcast Orbit Error with Respect to Precise Final Orbit

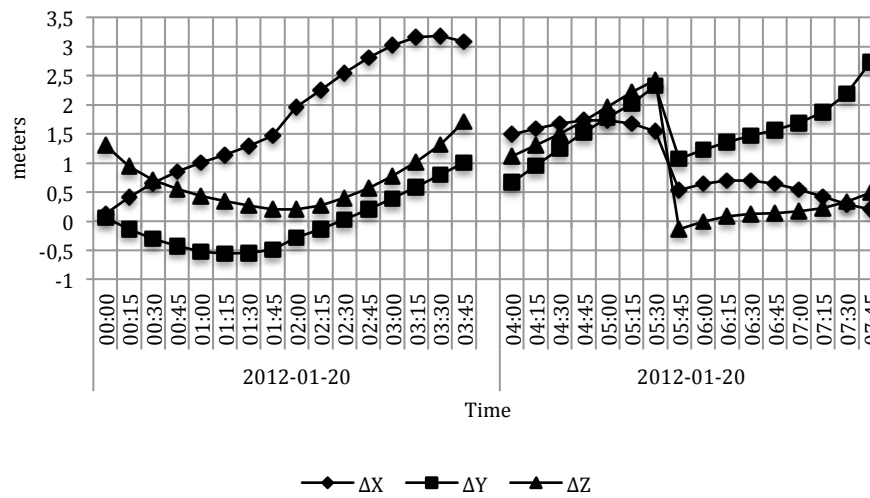


Fig. E1. PRN01 Broadcast orbit error with respect to IGS final orbit at 20.01.2012 between 00:00–08:00 time

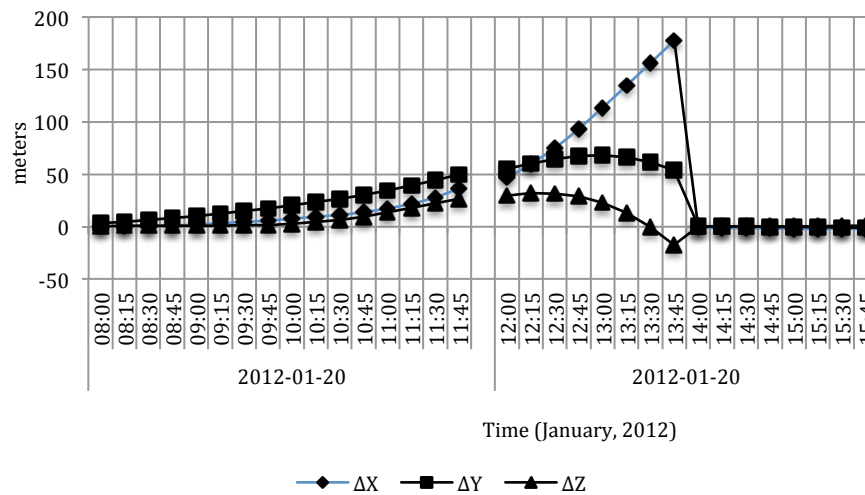


Fig. E2. PRN01 Broadcast orbit error with respect to IGS final orbit at 20.01.2012 between 08:00–16:00 time

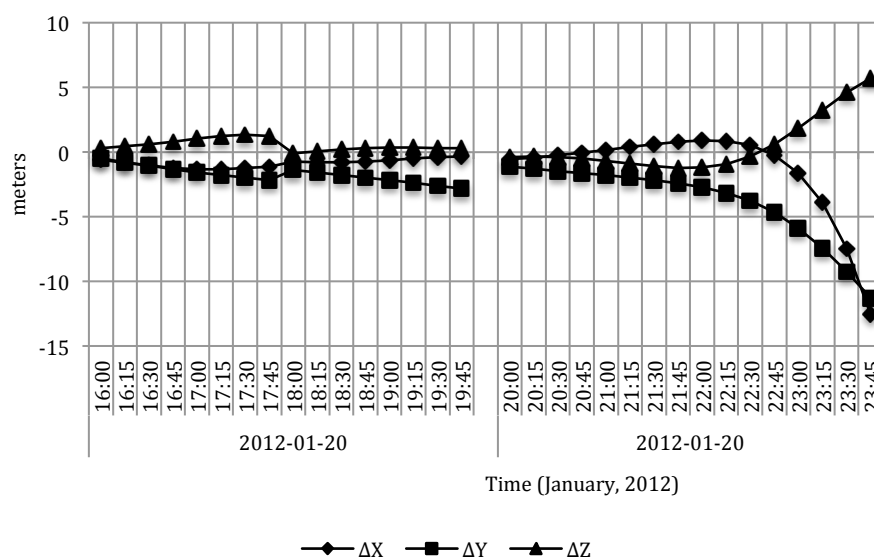


Fig. E3. PRN01 Broadcast orbit error with respect to IGS final orbit at 20.01.2012 between 16:00–24:00 time

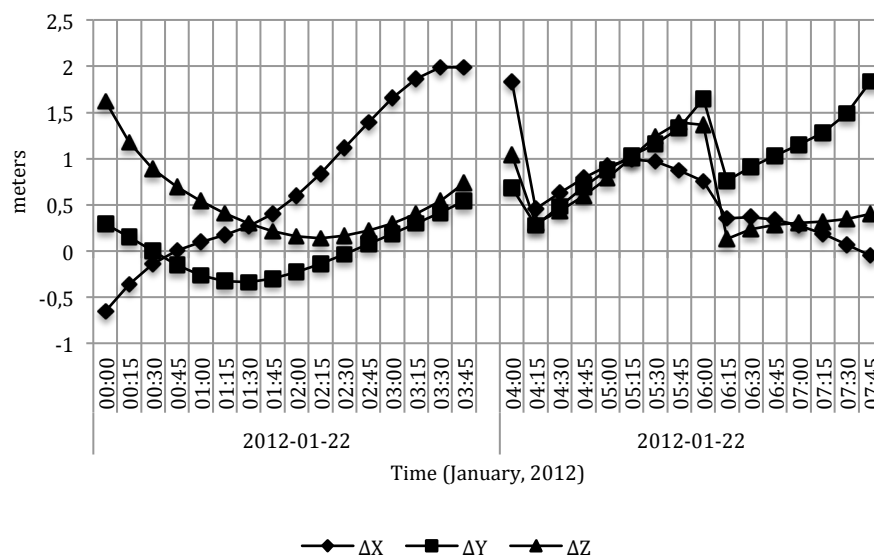


Fig. E4. PRN01 Broadcast orbit error with respect to IGS final orbit at 22.01.2012 between 00:00–08:00 time

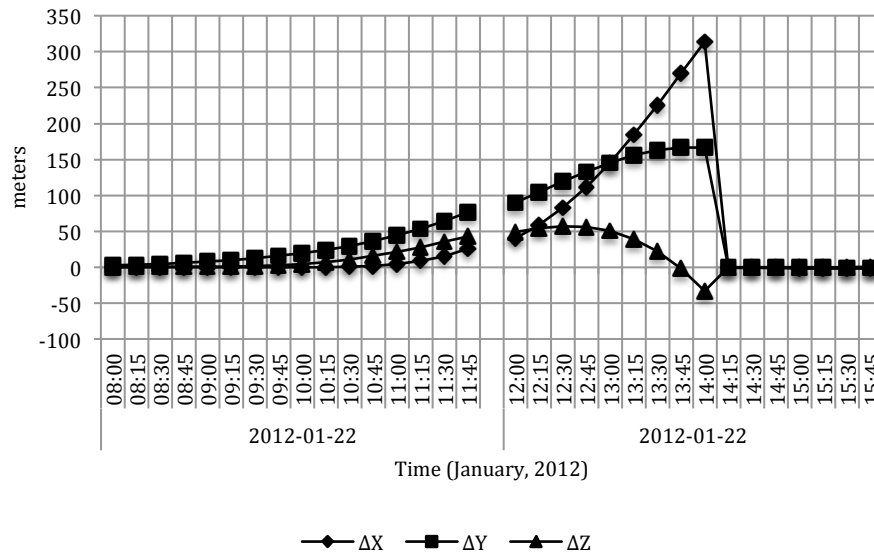


Fig. E5. PRN01 Broadcast orbit error with respect to IGS final orbit at 22.01.2012 between 08:00–16:00 time

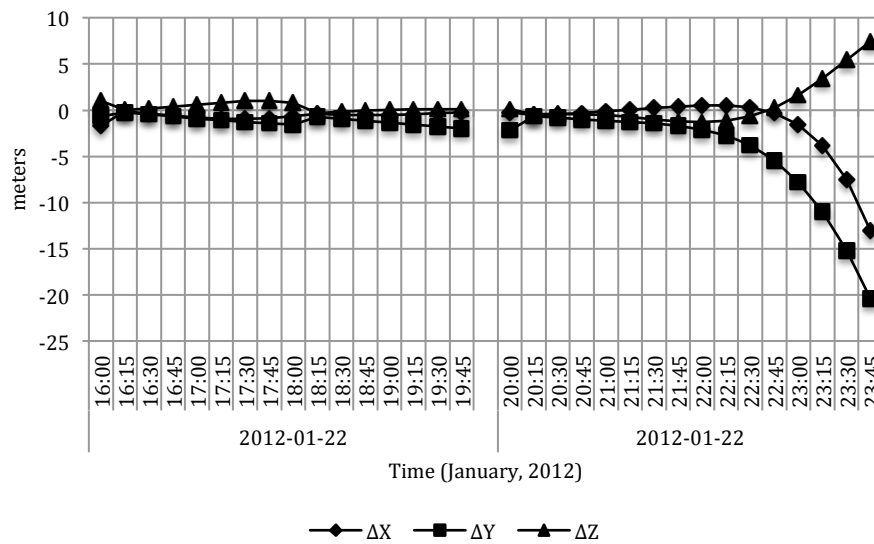


Fig. E6. PRN01 Broadcast orbit error with respect to IGS final orbit at 22.01.2012 between 16:00–24:00 time

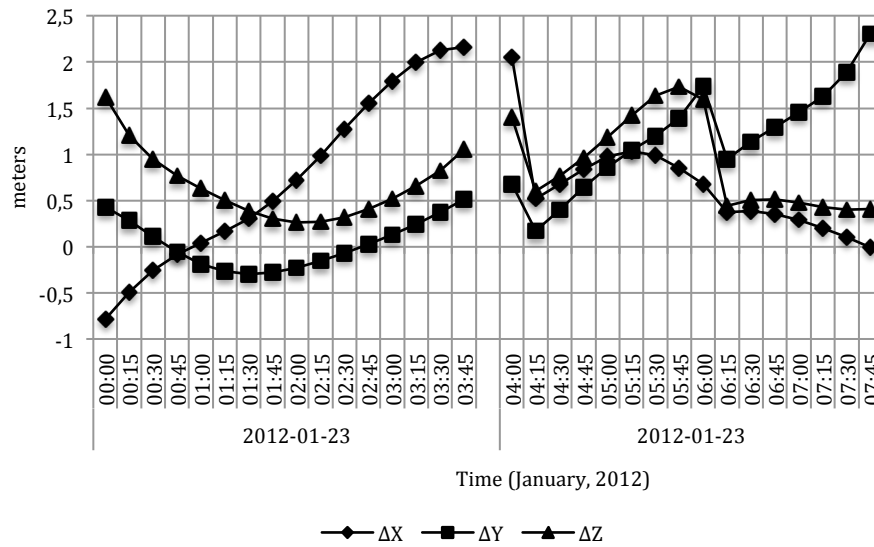


Fig. E7. PRN01 Broadcast orbit error with respect to IGS final orbit at 23.01.2012 between 00:00–08:00 time

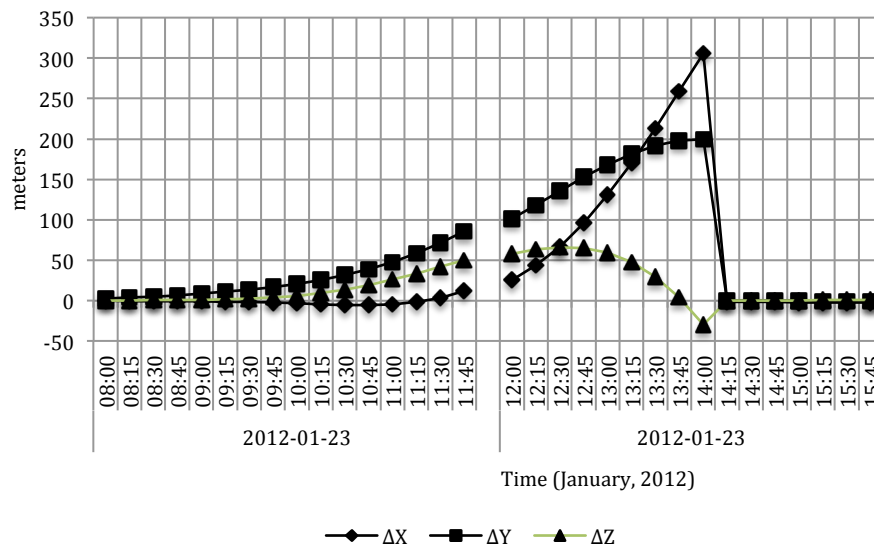


Fig. E8. PRN01 Broadcast orbit error with respect to IGS final orbit at 23.01.2012 between 08:00–16:00 time

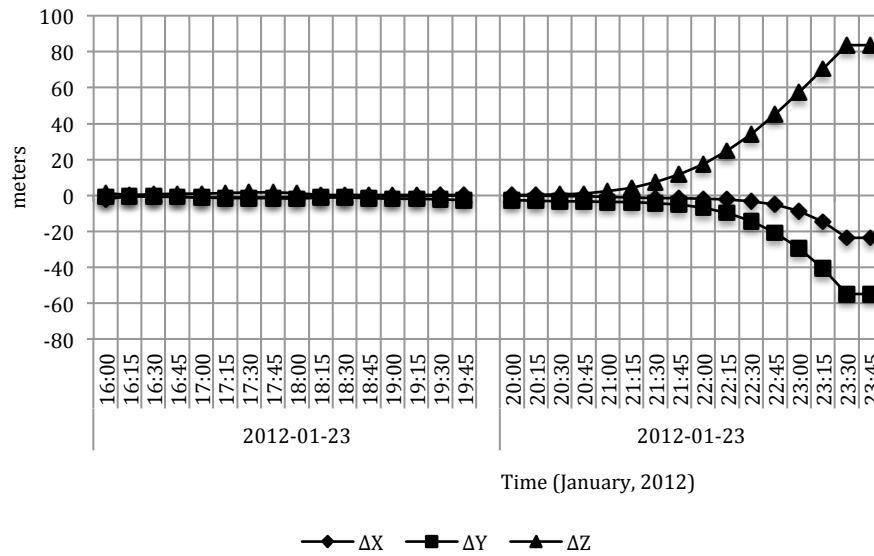


Fig. E9. PRN01 Broadcast orbit error with respect to IGS final orbit at 23.01.2012 between 16:00–24:00 time

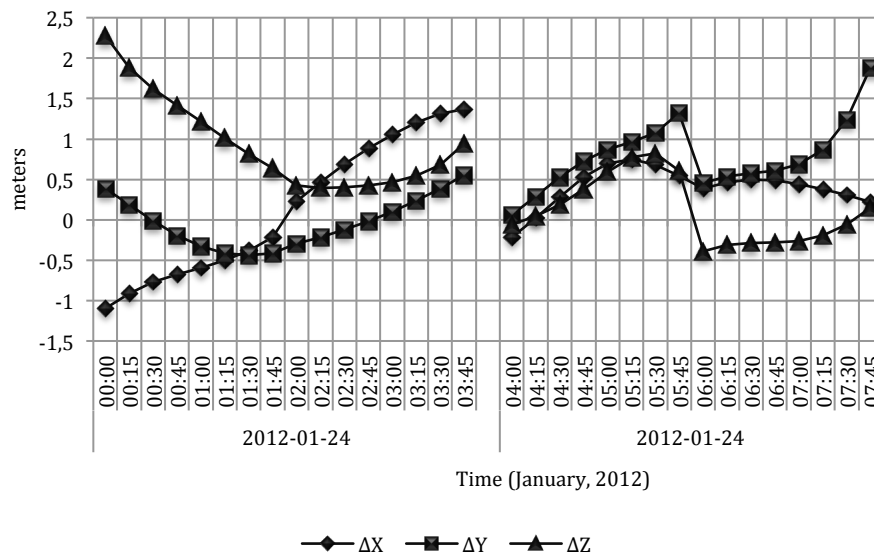


Fig. E10. PRN01 Broadcast orbit error with respect to IGS final orbit at 24.01.2012 between 00:00–08:00 time

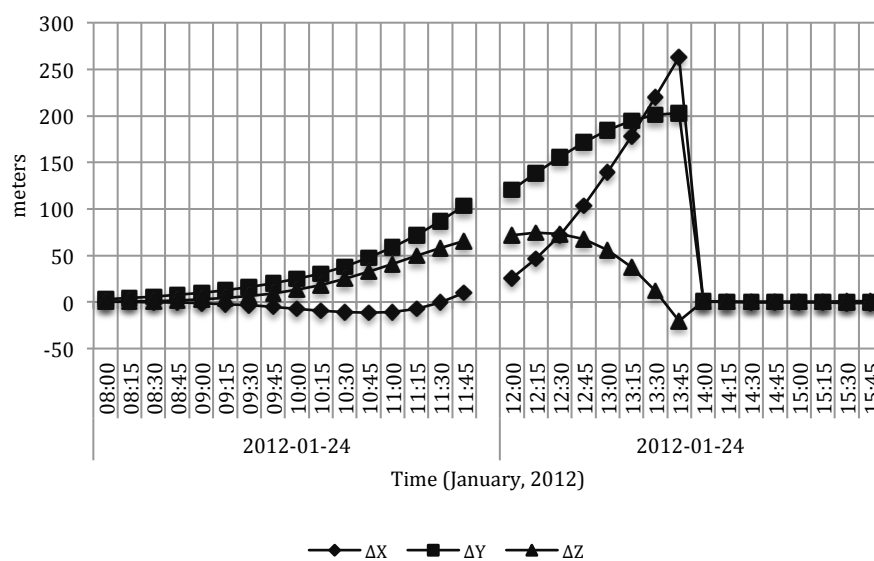


Fig. E11. PRN01 Broadcast orbit error with respect to IGS final orbit at 24.01.2012 between 08:00–16:00 time

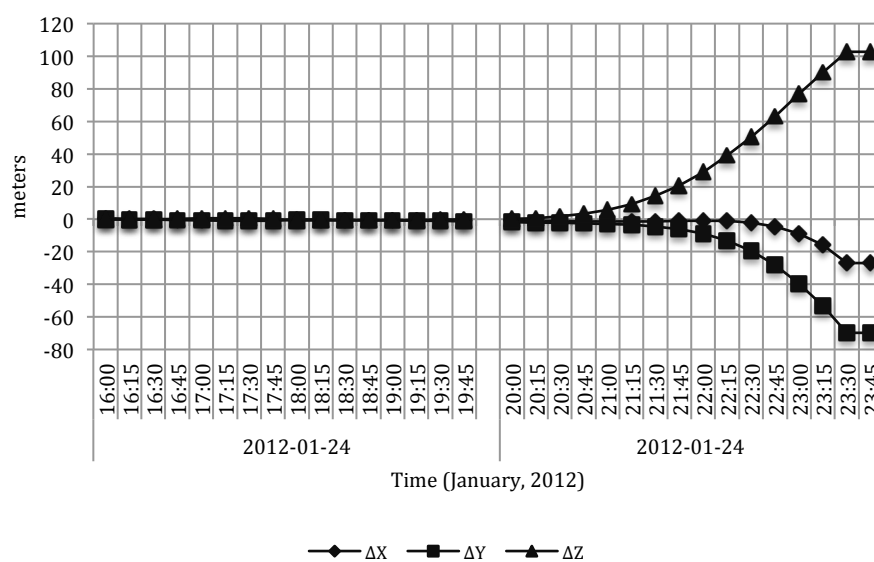


Fig. E12. PRN01 Broadcast orbit error with respect to IGS final orbit at 24.01.2012 between 16:00–24:00 time

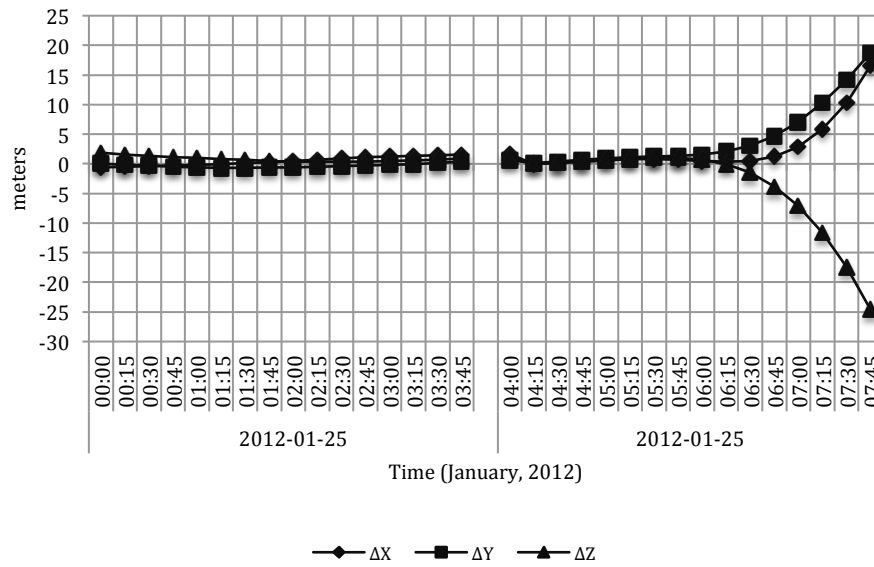


Fig. E13. PRN01 Broadcast orbit error with respect to IGS final orbit at 25.01.2012 between 00:00–08:00 time

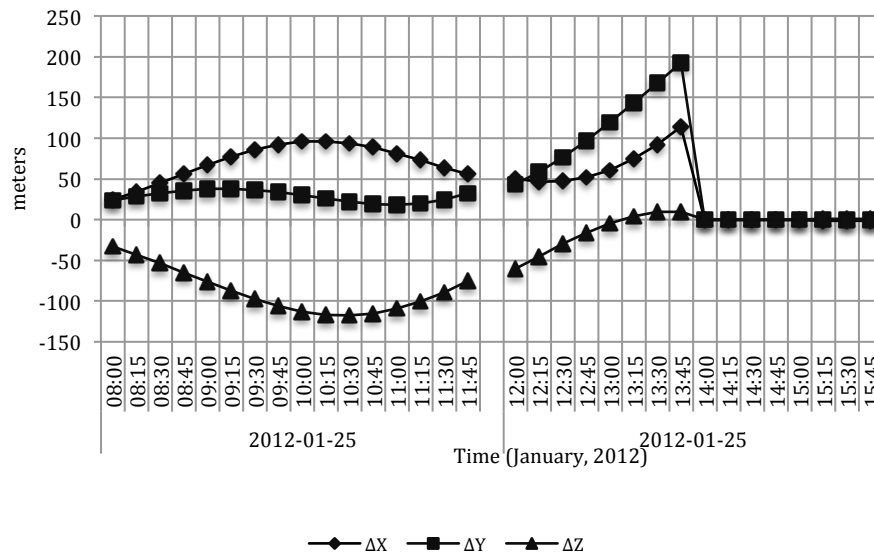


Fig. E14. PRN01 Broadcast orbit error with respect to IGS final orbit at 25.01.2012 between 08:00–16:00 time

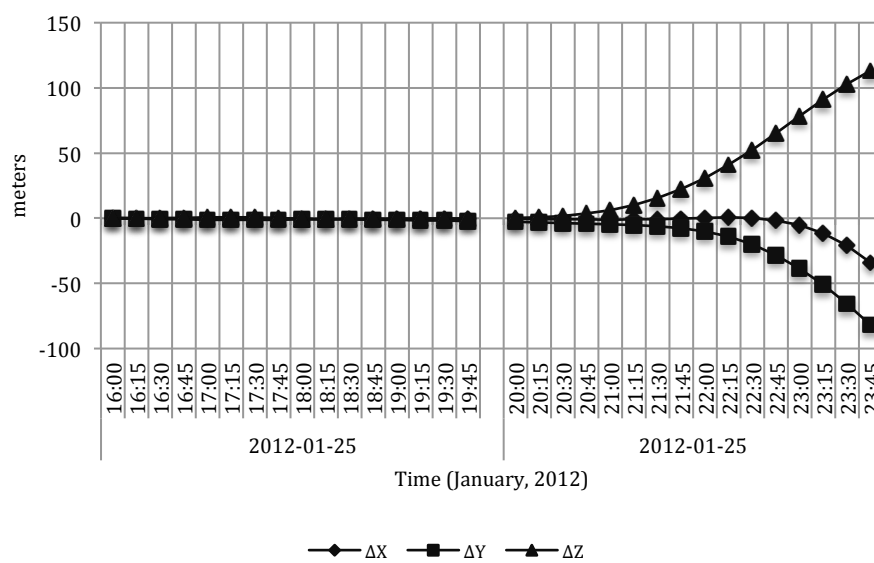


Fig. E15. PRN01 Broadcast orbit error with respect to IGS final orbit at 25.01.2012 between 16:00–24:00 time

THE ASSESSMENT OF THE INFLUENCE OF SOLAR STORMING
ON GEODETIC COORDINATES DETERMINED BY GLOBAL NAVIGATION
SATELLITE SYSTEM

Doctoral Dissertation

Technological Sciences,
Measurement Engineering (10T)

SAULĖS AUDRŲ ĮTAKOS GEODEZINĖMS KOORDINATĖMS, NUSTATOMOMS
GLOBALINE NAVIGACINE PALYDOVINE SISTEMA, TYRIMAS

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